



09/718,343



INVESTOR IN PEOPLE

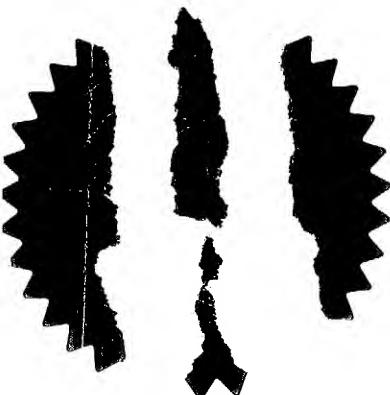
The Patent Office  
Concept House  
Cardiff Road  
Newport  
South Wales  
NP10 8QQ

I, the undersigned, being an officer duly authorised in accordance with Section 74(1) and (4) of the Deregulation & Contracting Out Act 1994, to sign and issue certificates on behalf of the Comptroller-General, hereby certify that annexed hereto is a true copy of the documents as originally filed in connection with the patent application identified therein.

In accordance with the Patents (Companies Re-registration) Rules 1982, if a company named in this certificate and any accompanying documents has re-registered under the Companies Act 1980 with the same name as that with which it was registered immediately before re-registration save for the substitution as, or inclusion as, the last part of the name of the words "public limited company" or their equivalents in Welsh, references to the name of the company in this certificate and any accompanying documents shall be treated as references to the name with which it is so re-registered.

In accordance with the rules, the words "public limited company" may be replaced by p.l.c., plc, P.L.C. or PLC.

Re-registration under the Companies Act does not constitute a new legal entity but merely subjects the company to certain additional company law rules.



Signed

*WT Evans.*

Dated 21 December 2000

Patents Form 1/77  
Patents Act 1977  
(Rule 16)



**The  
Patent  
Office**

## Request for grant of a patent

26NOV99 E494797-2 D02611  
F01/7700 0.00-9927907.7

The Patent Office  
Cardiff Road  
Newport  
Gwent NP9 1RH

1. Your reference

2641701/NF

2. Patent Application Number

**9927907.7**

3. Full name, address and postcode of the or of each applicant (*underline all surnames*)

Canon Kabushiki Kaisha  
30-2 3-Chome Shimomaruko  
Ohta-Ku  
Tokyo  
Japan

36301 0008

Patents ADP number (*if known*)

If the applicant is a corporate body, give the  
country/state of its incorporation

Country: JAPAN

State:

4. Title of the invention

IMAGE PROCESSING METHOD AND APPARATUS

5. Name of agent

Beresford & Co

"Address for Service" in the United Kingdom  
to which all correspondence should be sent

2/5 Warwick Court  
High Holborn  
London WC1R 5DJ

Patents ADP number

1826001

6. Priority details

Country

Priority application number

Date of filing

**Patents Form 1/77**

7. If this application is divided or otherwise derived from an earlier UK application give details

Number of earlier application                      Date of filing

8. Is a statement of inventorship and or right to grant of a patent required in support of this request?

YES

9. Enter the number of sheets for any of the following items you are filing with this form.

Continuation sheets of this form

Description                      97

Claim(s)                      17

Abstract                      1

Drawing(s)                      17 + 1

10. If you are also filing any of the following, state how many against each item.

Priority documents

Translations of priority documents

Statement of inventorship and  
right to grant of a patent (*Patents form 7/77*)                      YES                      1 + 1

Request for preliminary examination  
and search (*Patents Form 9/77*)

Request for Substantive Examination  
(*Patents Form 10/77*)

Any other documents  
(please specify)

11. I/We request the grant of a patent on the basis of this application

Signature Beresford & Co  
BERESFORD & Co

Date 25 November 1999

12. Name and daytime telephone number of  
person to contact in the United Kingdom                      NICHOLAS FOX

Tel:0171-831-2290

Patents Form 7/77  
Patents Act 1977  
(Rule 15)



The  
Patent  
Office

## Statement of inventorship and of right to grant of a patent

The Patent Office  
Cardiff Road  
Newport  
Gwent NP9 1RH

1. Your reference  
2641701/NF

2. Patent Application Number  
**9927907.7**

3. Full name of the or each applicant  
Canon Kabushiki Kaisha

4. Title of the invention  
IMAGE PROCESSING METHOD AND APPARATUS

5. State how the applicant(s) derived the right from the inventor(s) to be granted a patent

By virtue of the employment of the inventor by Canon Research Centre Europe Ltd, and by virtue of an agreement between Canon Research Centre Europe Ltd and Canon Kabushiki Kaisha dated 1 January 1994.

6. How many, if any additional Patents Forms  
7/77 are attached to this form?

7. I/We believe that the person(s) named over the page (and on any extra copies of this form) is/are the inventor(s) of the invention which the above patent application relates to.

Signature Beresford & Co Date 25 November 1999  
BERESFORD & Co

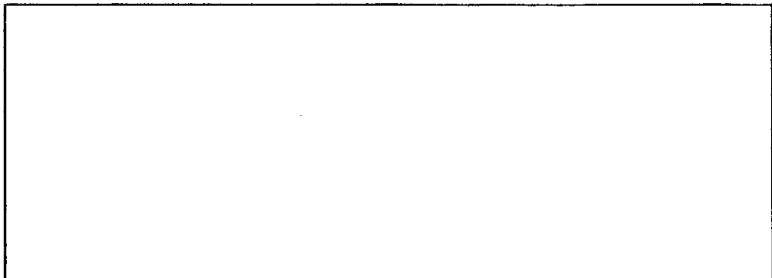
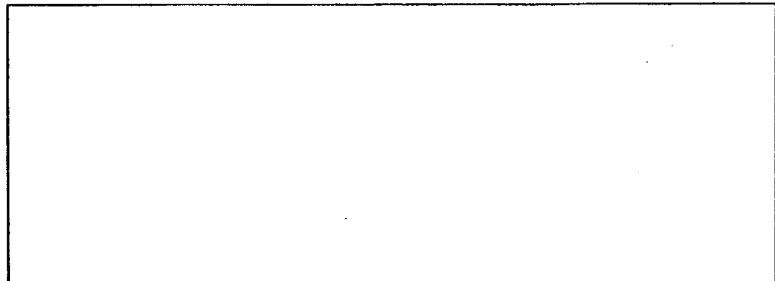
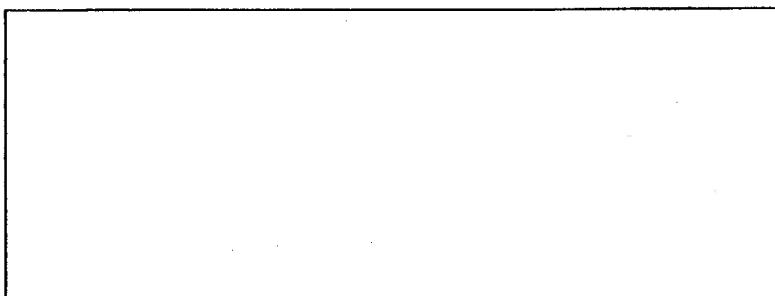
8. Name and daytime telephone number of  
person to contact in the United Kingdom  
NICHOLAS FOX  
Tel: 0171-831-2290

Patents Form 7/77

DR ADAM MICHAEL BAUMBERG

c/o Canon Research Centre Europe Ltd  
1 Occam Court  
Occam Road  
Surrey Research Park  
Guildford  
Surrey GU2 5YJ

7678816001



## IMAGE PROCESSING METHOD AND APPARATUS

The present invention relates to the detection and  
5 matching of features in images. The present invention  
may be used to match features in different images.  
Alternatively, the invention may be used to identify  
features in images for the purpose of for example  
indexing or categorisation.

10 The present invention is particularly suitable for the  
identification of points within images corresponding to  
the same physical point of an object seen from two  
viewpoints. By identifying points within images  
15 corresponding to the same physical point on an object, it  
is possible to establish the relative positions from  
which image data has been obtained. The image data can  
then be used to generate a three-dimensional model of the  
object appearing in the images.

20 The appearance of an object in an image can change in a  
number of ways as a result of changes of camera  
viewpoint. If points in images taken from different  
camera viewpoints are to be matched, it is therefore  
25 necessary to characterize points within images in a way  
which is not affected by the introduced distortion so  
that matching is possible.

A number of ways of characterizing features in images have been suggested. One example is the use of rotational invariants suggested by Gouet et al, in "A Fast Matching Method for Colour Uncalibrated Images Using Differential Invariants" British Machine Vision Conference, 98 Volume 1, page 367-376. This suggests characterizing feature points in images using differential texture invariants which are invariant under rotation. In this way, rotation of a camera may be accounted for. Furthermore, small variations in camera position give rise to distortions which may be approximated as rotations and hence the use of rotational invariants is also suitable to account for some other distortions.

However, some changes of viewpoint give rise to distortions which cannot be approximated to rotations. The matching of feature points in such images may therefore be unsatisfactory.

In one aspect, the present invention aims to provide an apparatus which more accurately matches feature points in images of the same object taken from different viewpoints.

In accordance with one aspect of the present invention there is provided an apparatus for matching features in images comprising:

input means for receiving image data;  
characterization means for characterizing points  
within images corresponding to received image data; and  
matching means for matching points within image data  
5 on the basis of the characterization of points  
characterized by said characterization means,  
characterized in that:

10 said characterization means is arranged to  
characterize points within images, wherein said  
characterization is substantially unaffected by affine  
distortions of a portion of an image centred on said  
feature point.

15 When images of planar surfaces are taken from different  
positions relative to the surface, the surfaces appear to  
undergo affine transformations. By providing an  
apparatus which characterizes portions of images in a way  
which is substantially unaffected by affine distortions  
the matching of points on planar surfaces of objects in  
20 images taken from different view points can be improved.

Another embodiment of the present invention comprises an  
apparatus for comparing an image against a database of  
images utilizing apparatus for matching feature points in  
25 the images, as has been described above.

Further aspects and embodiments of the present invention  
will become apparent when reading the following

description with reference to the accompanying drawings  
in which:

5      Figure 1 is a block diagram of a modular system for  
generating three-dimensional computer models from images  
of objects in which the present invention may be  
embodied;

10     Figures 2A and 2B are a pair of illustrative examples of  
images of an object taken from two different viewpoints;

15     Figures 3 and 4 are a further pair of illustrative  
examples illustrating the effect of changing camera  
viewpoint;

Figure 5 is a block diagram of a feature detection and  
matching module in accordance with the first embodiment  
of the present invention;

20     Figure 6 is a flow diagram of the processing of the  
control module program of the feature detection and  
matching module of Figure 5;

25     Figures 7A and 7B are a flow diagram of the processing of  
data in accordance with the detection module program of  
the feature detection and matching module of Figure 5;

Figure 8 is a flow diagram of the processing of the

characterization module of the feature detection and matching module of Figure 5;

Figures 9A, 9B and 9C are a flow diagram of the  
5 calculation of rotational invariants by the characterization module;

Figures 10, 11, 12A, 12B, 13A and 13B are illustrative examples of the distribution of scaling factors used in  
10 scaling masks to calculate approximations of complex coefficients for the calculation of rotation invariants;

Figure 14 is a flow diagram of the processing of the matching module of the feature detection and matching  
15 module of Figure 5;

Figure 15 is a block diagram of an apparatus for retrieving images from a database of images utilizing a characterization and matching module in accordance with  
20 a third embodiment of the present invention; and

Figure 16 is a block diagram of an apparatus for generating images in which the effects of stretch and skew resulting from affine transformations of an image  
25 are removed in accordance with a fifth embodiment of the present invention.

FIRST EMBODIMENT

Figure 1 schematically shows the components of a modular system in which the present invention may be embodied. These components can be effected as processor-implemented  
5 instructions, hardware or a combination thereof.

Referring to Figure 1, the components are arranged to process data defining images (still or moving) of one or more objects in order to generate data defining a three-dimensional computer model of the object(s).  
10

The input image data may be received in a variety of ways, such as directly from one or more digital cameras, via a storage device such as a disk or CD ROM, by  
15 digitisation of photographs using a scanner, or by downloading image data from a database, for example via a data link such as the Internet, etc.

The generated 3D model data may be used to: display an  
20 image of the object(s) from a desired viewing position; control manufacturing equipment to manufacture a model of the object(s), for example by controlling cutting apparatus to cut material to the appropriate dimensions; perform processing to recognise the object(s), for  
25 example by comparing it to data stored in a database; carry out processing to measure the object(s), for example by taking absolute measurements to record the size of the object(s), or by comparing the model with

models of the object(s) previously generated to determine changes therebetween; carry out processing so as to control a robot to navigate around the object(s); store information in a geographic information system (GIS) or 5 other topographic database; or transmit the object data representing the model to a remote processing device for any such processing, either on a storage device or as a signal (for example, the data may be transmitted in virtual reality modelling language (VRML) format over the 10 Internet, enabling it to be processed by a WWW browser); etc.

The feature detection and matching module 2 is arranged to receive image data recorded by a still camera from 15 different positions relative to the object(s) (the different positions being achieved by moving the camera and/or the object(s)) or frames from a video camera, where there is an interruption and change of view point within a stream of video images such as arises when a 20 user switches off a video camera and restarts filming an object from a different position. The received data is then processed in order to match features within the different images (that is, to identify points in the images which correspond to the same physical point on the 25 object(s)).

The feature detection and tracking module 4 is arranged to receive image data recorded by a video camera as the

relative positions of the camera and object(s) are changed (by moving the video camera and/or the object(s)). As in the feature detection and matching module 2, the feature detection and tracking module 4 5 detects features, such as corners, in the images. However, the feature detection and tracking module 4 then tracks the detected features between frames of image data in order to determine the positions of the features in other images.

10

The camera position calculation module 6 is arranged to use the features matched across images by the feature detection and matching module 2 or the feature detection and tracking module 4 to calculate the transformation 15 between the camera positions at which the images were recorded and hence determine the orientation and position of the camera focal plane when each image was recorded.

The feature detection and matching module 2 and the 20 camera position calculation module 6 may be arranged to perform processing in an iterative manner. That is, using camera positions and orientations calculated by the camera position calculation module 6, the feature detection and matching module 2 may detect and match 25 further features in the images using Epipolar geometry in a conventional manner, and the further matched features may then be used by the camera position calculation module 6 to recalculate the camera positions and

orientations.

If the positions at which the images were recorded are already known, then, as indicated by arrow 8 in Figure 1,  
5 the image data need not be processed by the feature detection and matching module 2, the feature detection and tracking module 4, or the camera position calculation module 6. For example, the images may be recorded by mounting a number of cameras on a calibrated rig arranged  
10 to hold the cameras in known positions relative to the object(s).

Alternatively, it is possible to determine the positions of a plurality of cameras relative to the object(s) by  
15 adding calibration markers to the object(s) and calculating the positions of the cameras from the positions of the calibration markers in images recorded by the cameras. The calibration markers may comprise patterns of light projected onto the object(s). Camera  
20 calibration module 10 is therefore provided to receive image data from a plurality of cameras at fixed positions showing the object(s) together with calibration markers, and to process the data to determine the positions of the cameras. A preferred method of calculating the positions  
25 of the cameras (and also internal parameters of each camera, such as the focal length etc) is described in "Calibrating and 3D Modelling with a Multi-Camera System" by Wiles and Davison in 1999 IEEE Workshop on Multi-View

Modelling and Analysis of Visual Scenes, ISBN 0769501109.

The 3D object surface generation module 12 is arranged to receive image data showing the object(s) and data defining the positions at which the images were recorded, and to process the data to generate a 3D computer model representing the actual surface(s) of the object(s), such as a polygon mesh model.

10 The texture data generation module 14 is arranged to generate texture data for rendering onto the surface model produced by the 3D object surface generation module 12. The texture data is generated from the input image data showing the object(s).

15 Techniques that can be used to perform the processing in the modules shown in Figure 1 are described in EP-A-0898245, EP-A-0901105, pending US applications 09/129077, 09/129079 and 09/129080, the full contents of which are 20 incorporated herein by cross-reference, and also Annex A.

The present invention may be embodied in particular as part of the feature detection and matching module 2 (although it has applicability in other applications, as 25 will be described later).

Prior to describing in detail a feature detection and characterization module 2 in accordance with a first

embodiment of the present invention, the problems of accurately matching points within images of an object seen from different viewpoints arising due to the differences in appearance resulting from a change of view point of an object will briefly be discussed.

Figures 2A and 2B are illustrative examples of two images recorded by a still camera from different positions relative to the same object. In this example the image 10 20 of Figure 2A comprises an image of a house 22 as viewed from in front. In the image can be seen four windows 24,26,28,30, a front door 32 and a chimney 34. Next to the house to the right of the house there is a flower 36.

15 The image 40 of Figure 2B comprises an image of the same house 42 taken from a viewpoint to the left of the position in which the first image 20 has been taken. Again visible in the image are four windows 44,46,48,50, 20 a front door 52 and a chimney 54. A flower 56 is also visible to the right of the house 42.

As an initial step for establishing the relative camera positions between two images of the same object, it is 25 necessary to establish which points in the images correspond to the same physical points of the objects appearing within the images. Where a sequence of images are taken with a video camera the differences between

consecutive images, unless there is an interruption in the video image stream, are usually very small. It is therefore possible, provided there has been no interruption in the video image stream, to constrain the  
5 search for points in images which correspond to the same physical point on an object to a small area in the same region of a second image and then determine the effect of moving the camera in terms of a translation applied to pixels within that portion of the image.

10

In contrast, where a still camera is used to obtain image data of objects from different viewpoints or where a video camera has been switched off between two image frames in the video stream the difference between the  
15 view point in two images can be much larger. As the difference in viewpoints increases it is no longer adequate to assume that the change in viewpoint can be approximated as a translation of portions of an image since in addition to translation the parts of an image  
20 are also distorted as a result of the change of view point.

Thus for example looking at the exemplary images of Figures 2A and 2B it is apparent that the square windows  
25 24,26,28,30 appearing in the image 20 of Figure 2A are stretched and skewed so as to appear as parallelograms 44,46,48,50 in the image 40 of Figure 2B. This is in addition to the windows 44,46 on the left hand side of

the house being translated further down the image and the window 48,50 on the right hand side of the house being translated up in the image 40 of Figure 2B compared to the same windows 24-30 in the image 20 of Figure 2A.

5 Furthermore, in contrast to the appearance in the image 20 of Figure 2A, in the image 40 of Figure 2B because the windows 44,46 on the left hand side of the house are now closer to the camera than the windows 48,50 on the right hand side of the house, the relative proportions of the 10 windows has changed with the windows 44,46 on the left hand side of the house in the second image 40 being larger than the windows 48,50 on the right hand side of the house.

15 Since the appearance of an object can change significantly it is necessary to identify characteristics of an image which are not affected by the distortions resulting from a change of viewpoint. By characterizing points within an image which are not significantly 20 affected by the distortions of the appearance of an image resulting from changes in camera position, it is possible to use the characterization of an image to establish which points within pairs of image correspond to the same physical points on an object.

25 Figures 3 and 4 are two further exemplary images to illustrate a further problem with the matching of the points in images corresponding to the same physical

points on an object. One of the problems of matching feature points in images of an object arises from the possibility that an object in one image may appear as a smaller or larger object in another image due to the fact  
5 that the two images have been taken from camera positions further or closer to an object.

Figure 3 is an image showing a building block 100 in the foreground of a window 102 in the background with a  
10 landscape 104 visible through the window. The window panes of the window 102 form a cross at the centre of the window where they meet.

Figure 4 is an example of an image of the same scene  
15 taken from the camera viewpoint much closer to the building block 100. In the image of Figure 4 the building block 100 appears to be much larger than it does in the image of Figure 3.

20 The possibility that objects may appear to be of different sizes in different images due to a change of camera viewpoint gives rise to two separate problems when attempting to establish correspondence between points in one image and points in another image.

25

The first problem arising from changes of camera viewpoint that may cause a change of scale is that a change of scale may cause different points of interest to

be selected for future characterization, thus making future matching impossible. This problem arises because some large scale features such as the cross at the centre of the image of Figure 3 may only become apparent when a  
5 large area of an image is considered. However, if only large areas of images are considered for the detection of points of interest, smaller feature points such as the corners of the building block 100 as it appears in Figure 3 may be overlooked. However, where changes of scale are  
10 likely to occur it is necessary that both large and small features are detected since these may subsequently appear as small or large features in future images. Thus for example the small feature that appears as the corner of the building block 100 in the image of figure 3 appears  
15 as a far larger feature in the image of Figure 4.

The second problem arising due to changes of scale arises after a selection of features of interest has been made. When feature points of interest have been selected, the  
20 features need to be characterized so that matching may occur. If features appearing as a large feature in one image are to be matched with the features which appear as a small feature in another image, it can be important to account for the fact that the features appear at different sizes as the characterization of a feature may vary due to the apparent size of the feature in an image.  
25 If no allowance is made for the possibility that the same feature may appear at different scales in different

images when characterizing features the characterization of an image feature may be dependent on the size at which it appears and hence matching different sized representations of the same image may be impossible using  
5 such characterizations.

The present embodiment includes a feature matching and detection module 2 which provides a number of means by which differences in images arising from a change of  
10 camera viewpoint can be accounted for and hence enabling matching of features appearing in images taken from spaced view points to be facilitated as will now be described.

15 FEATURE DETECTION AND MATCHING MODULE

Figure 5 is a block diagram of a feature detection and matching module 2 in accordance with the first embodiment of the present invention. The feature detection and matching module 2 in this embodiment is arranged to receive grey scale image data recorded by a still camera from different positions relative to an object or video image data where an interruption in a video stream has occurred and filming has restarted from a different position and to output a list of pairs of co-ordinates of  
20 points in different images which correspond to the same physical point of the object appearing in the images. The list of pairs of co-ordinates can then be used by the camera position calculation module 6 to determine the  
25



orientation and position of the camera focal plane when each image was recorded. In this embodiment the feature matching and detection module 2 is arranged to perform processing iteratively with the camera position calculation module 6 to match image feature points utilizing calculated camera positions and then refine calculated camera positions on the basis of those matched feature points.

10 The feature detection and matching module 2 comprises an image buffer 60 for receiving grey scale image data, comprising pixel data for images, and camera position data from the camera position calculation module. The image buffer 60 is connected to an output buffer 62 via a central processing unit (CPU) 64 which is arranged to process the image data stored in the image buffer 60 to generate a list of matched points output to the output buffer 62. The processing of image data by the CPU is in accordance with a set of programs stored within a read only memory (ROM) 66 which is connected to the CPU 64. In this embodiment the feature detection and matching module 2 is arranged to receive and process images of 768 by 576 pixels.

15 20 25 The programs stored in the ROM 66 comprise a control module 70 for coordinating the overall processing of the programs stored in the ROM 66, a detection module 72 for identifying features to be matched between images, a

characterization module 74 for characterizing the features detected by the detection module 72 and a matching module 76 for matching features detected by the detection module 72 on the basis of the characterization 5 of those features by the characterization module 74.

The CPU 64 is also connected to a random access memory (RAM) 78 which is used for the storage of variables calculated in the course of detecting features in images, 10 characterizing those features and matching them to generate an output list of matched points between pairs of images.

Figure 6 is a flow diagram of the control module program 15 70 for coordinating the flow of control of the processing of data by the feature detection and matching module 2. Initially the control module 70 waits until image data is received (S1) and stored in the image buffer 60. This causes the control module 70 to invoke the detection 20 module 72 to analyse the image data stored in the image buffer 60 to ascertain (S2) a number of feature points within the images stored in the image buffer 60 which are to be further processed to determine whether they can be matched as correspond to the same physical point on an object in two images stored within the image buffer 60 as will be described in detail later. The co-ordinates of 25 the potential feature points of interest detected in the images stored in the image buffer 60 are then stored in

RAM 78 together with other data relating to the feature points for use in the subsequent processing by the CPU 64 as will be described later.

5 When the feature points for a pair of images have been determined and stored in RAM 78 the control module 70 then invokes the characterizing module 74 to characterize (S3) each of the detected feature points using portions of the images around detected feature points as will be  
10 described in detail later. Data representative of the characterization of each of the feature points is then stored in RAM 78 so that it may be used to match points in different images as corresponding to the same physical point in an object appearing in the images.

15 When all of the feature points in a pair of images have been characterized by the characterization module 74 the control module 70 then invokes the matching module 76 to match (S4) the feature points characterized by the  
20 characterization module 74 in different images as corresponding to the same physical point on an object on the basis of the characterization data stored in RAM 78.

After the matching module 76 has determined the best  
25 matches for feature points characterized by the characterization module 74 the control module 70 causes a list of pairs of matched feature points to be output (S5) to the output buffer 62.

FEATURE DETECTION

The detection module 72 is arranged to process image data stored in the image buffer 60 to select a number of feature points which are candidates for matching by the 5 characterization module 74 and the matching module 76.

As part of the processing of image data to select feature points, the detection module 72 is arranged to generate smoothed image data by averaging values across a number 10 of pixels to eliminate small features and to calculate feature strength values indicating the presence of features utilizing only limited areas of a smoothed image to eliminate large features. By linking these processes to a scaling factor and processing the image data for 15 each of a predefined set of scaling factors, features of different sizes are detected and assigned feature strengths. In order that comparisons of feature strength can be made regardless of the scale factor which was used in the process to detect a feature, these feature 20 strength values are calculated utilizing the selected scale factor to enable comparison of the strengths of features of different sizes as will now be described.

Figures 7A and 7B are a flow diagram of the processing of 25 data in accordance with the detection module 72 stored in ROM 66. In this embodiment of the present invention the feature points of images stored within the image buffer 60 are selected on the basis of processing the image data

to detect points within the images representative of corners on objects within the images.

Initially (S10) the detection module 72 causes the CPU 64  
5 to calculate a smoothed set of image data based on the  
image data stored in the image buffer 60. In order to  
calculate a grey scale value for each pixel in the  
smoothed image, the sum of the grey scale pixel values  
of a region of the image centred on corresponding pixels  
10 in the image data is determined where the contribution of  
each pixel in that region of the image is scaled in  
accordance with a Gaussian function  $G(x,y)$  where:

$$G(x,y)=\exp^{-\frac{(x^2+y^2)}{\sigma_s^2}}$$

15 where  $x$  and  $y$  are the relative  $x$  &  $y$  coordinates of a  
pixel relative to the pixel for which a value in the  
smoothed image is to be calculated and  $\sigma_s$  is the first of  
the set of scale factors stored in memory. In this  
embodiment the detection module 72 is arranged to detect  
20 features using a stored set of scale factors comprising  
the values of 0.5, 0.707, 1.414, 2, 2.828 and 4 with the  
first scale factor being 0.5. Each of the scale factors  
is associated with stored window size of square regions  
for calculating smoothed images and averaged second  
25 moment matrices at an associated scale as will now be

described.

By calculating a smoothed image from the image data stored in the image buffer 60 a set of image data is  
5 obtained where the values for pixels in the smoothed image are dependent upon regions within the image. This has the effect of eliminating from the image data representing very small features which might otherwise be detected as a corner in the future processing of the  
10 image.

The scale at which an image is smoothed determines the extent to which the pixel value for a pixel in the smoothed image is determined by neighbouring pixels.  
15 Where a small value is selected for  $\sigma_s$ , the effect of scaling is such that the contribution of other pixels reduces rapidly as the pixels get further away. Thus the value for a corresponding pixel in the smoothed image may be determined by only considering a small region of image  
20 data centred on a pixel with the contribution of pixels outside of that region being ignored. In contrast, for larger values  $\sigma_s$  the contribution of more distant pixels in the image data is more significant. It is therefore no longer appropriate to ignore the contributions of  
25 these more distant pixels. A larger number of pixels in the image data must therefore be considered for the calculation of pixel values in a smoothed image at such larger scale.

Thus in this embodiment of the present invention when calculating a smoothed image at a scale associated with a small value of  $\sigma_s$  a  $3 \times 3$  region of pixels centred on a pixel in the original image is used to determine a 5 value of the corresponding pixel in the smoothed image. For larger values of  $\sigma_s$  progressively larger square regions are used with the size of the region being selected so that the scaling for those pixels whose contribution is not calculated is less than a threshold 10 value for example  $e^{-8}$ . As stated previously each of these window sizes is stored in association with a scale factor and utilised automatically when the associated scale factor is utilised to generate a smoothed image.

15 When a smoothed image has been calculated and stored in memory 78 the detection module 72 then causes (S12) the CPU 64 to calculate for each pixel in the smoothed image a second moment matrix M where:

$$M = \begin{pmatrix} I_x^2 & I_x I_y \\ I_x I_y & I_y^2 \end{pmatrix}$$

20 where  $I_x$  and  $I_y$  are derivatives indicative of the rate of change of grey scale pixel values for pixels in the smoothed image along x and y coordinates respectively calculated in a conventional manner by determining the 25 difference between grey scale values for adjacent pixels.

The calculated values for the second moment matrices for each of the pixels in the smoothed image are then stored in the memory 78 for future processing.

5 The detection module 72 then causes (S14) an averaged second moment matrix for each of the pixels in a region to be calculated by the CPU 64. These averaged second moment matrices are calculated in a similar manner to the calculation of the smoothed image in that the averaged 10 second memory matrix for a pixel is calculated from the sum of the second moment matrices for pixels in a square region centred on a selected pixel scaled by a scaling factor  $G(x,y)$  where:

$$15 \quad G(x,y) = \exp \frac{-(x^2 + y^2)}{2\sigma_t^2}$$

where  $x$  and  $y$  are the relative  $x$  &  $y$  coordinates of a pixel in a square region centred on the pixel for which an averaged second moment matrix image is to be calculated and  $\sigma_t$  is a scale factor selected from a stored 20 set of scale factors.

As has previously been stated in relation to the calculation of a smoothed image from received image data since the scale selected for an averaging operation

determines the rate at which contributions from surrounding pixels declines, the selected scale also determines size of the region centred on a pixel which is relevant for determining the average as the scaled 5 contribution of more distant pixels ceases to be of importance. Thus as in the case of the calculation of the smoothed image only a limited number of second moment matrices for pixels adjacent to a selected pixel need to be determined with those pixels whose contribution scaled 10 by a factor of less than a threshold value, in this embodiment  $e^{-8}$  being ignored.

In this embodiment of the present invention the scale  $\sigma_t$  at which second moment matrices in a region are 15 determined is set to be equal to  $2 \sigma_s$ . In this way the value determined for an averaged second moment matrix centred on a pixel is determined on the basis of the second moment matrices for pixels in a square region whose size is dependent on the value of  $\sigma_s$  which is 20 selected. Similarly the size of a region is selected by utilising a window size stored in association with a scale factor, which is twice the size of the window size used for generating a smoothed image with the same associated scale factor.

25

The combined effect of the smoothing operation to generate smoothed image and the subsequent averaging operation to calculate an averaged second moment matrix

is to restrict the size of features which are detected by the detection module 72. Both operations, since they involve the determining of a calculated value for a pixel utilizing a region of an image act to eliminate the 5 effect of small features whose effect is spread by the averaging process. However, since both processes only calculate values for pixels based on fixed regions of image data, features in the original image which are only apparent when larger regions of image data are considered 10 will also be effectively filtered by the detection module 72. Thus the averaged second moment matrices calculated for each pixel are representative of features in the original image, which have a size lying within a range defined by  $\sigma_s$ .

15

For each of the pixels for which an averaged second moment matrix has been calculated a normalised corner strength is then determined (S16) by the detection module 72. In this embodiment the normalised corner strength 20 comprises a calculated value for a Harris corner detector scaled by  $\sigma_s^{-4}$ . The normalised corner strength for a pixel is calculated using the following equation:

25

$$\text{NormalisedCornerStrength} = \frac{1}{4} \frac{[\det M_A - 0.04 * (\text{trace} M_A)^2]}{\sigma_s^4}$$

where  $M_A$  is the averaged second moment matrix calculated for a pixel.

The calculated normalised corner strength for a pixel,  
the average second moment matrix and the co-ordinate of  
the pixel are then stored (S18) in memory 78. In this  
embodiment the normalised corner strength is used for  
5 selecting feature points for further characterization as  
will be described later. The averaged second moment  
matrix is used in the subsequent processing of selected  
feature points as will also be described later. By  
storing the value of the averaged second moment matrix  
10 the necessity of having to recalculate this matrix  
subsequently is avoided.

By calculating the normalised corner strength in the  
manner described above the calculated normalised corner  
15 strength is independent of the values selected for  $\sigma_s$ ,  
since the difference in the values in  $M_A$  arising from the  
determination of an averaged second moment matrix for a  
smoothed image across a region dependent upon a selected  
value for  $\sigma_s$  are accounted for by making the normalised  
20 corner strength proportional to  $\sigma_s^{-4}$ .

Thus if two different sized regions in two images  
correspond to the same object taken from view points at  
different distances from the object the calculated  
25 normalised corner strengths for the same physical point  
on an object will be comparable. Therefore by selecting  
a set of feature points for further characterization on  
the basis of the calculated normalised corner strengths,

the same feature points can be selected regardless of the actual scale at which those features are detectable and hence the same features should be selected regardless of the apparent changes of size of an object due to changes  
5 of view point.

The calculated normalised corner strength for a pixel is indicative of a relative measure of the extent to which a region of an image centred on a point is indicative of  
10 a corner. Where a pixel is associated with a normalised corner strength is greater than its neighbours, this indicates that the pixel corresponds most closely to a point which has the appearance of a corner. In order to identify those points within an image which most strongly  
15 correspond to corners, the detection module 72 compares calculated normalised corner strengths for each pixel with the calculated normalised corner strengths for the neighbouring pixels. In this embodiment this is achieved by the detection module 72 first determining (S20)  
20 whether normalised corner strengths have been stored for all the adjacent pixels in the region of the image for which the locations of normalised corner strength maxima are currently being determined. If the normalised corner strength has not yet been calculated for all adjacent  
25 pixels in this region of an image, the next pixel (S22) is selected and an average second moment matrix for that pixel and normalised corner strength is calculated and stored (S22, S14-S18).

When the detection module 72 determines (S20) that normalised corner strengths have been determined for all pixels in the current region for which the local corner strength maxima are to be calculated, the detection 5 module 72 then determines (S24) which of the pixels correspond to local maxima of normalised corner strength. The co-ordinates of these local maxima are then stored in the memory 78 together with the associated normalised corner strength, the averaged second moment matrix 10 calculated for that pixel, and the scale  $\sigma_s$  at which the corner was detected.

When the local maxima for a region of an image have been determined, the detection module 72 then checks (S26) 15 whether the region of the image for which corner strengths are currently being calculated corresponds to the last region of an image for which local corner strength maxima are determined. If the region of an image for which corner strengths are currently being 20 determined is not the last region of an image for determining corner strength the detection module 72 then updates the areas of memory 78 storing data relating the normalised corner strengths for those pixels which are no longer necessary for determining the value for local 25 maxima in the subsequent regions of the image to indicate that they may be reused and then calculates further normalised corner strengths (S28, S14-20) in the next region of the image and then determines and stores local

maxima of corner strength for that region (S24).

The determination of local maxima region by region therefore enables data which is no longer necessary to  
5 determine local maxima to be overwritten and hence minimises the memory required for the determination of which pixels correspond to local maxima and hence are most representative of corners in the original image.

- 10 If the detection module 72 determines (S26) that the pixels corresponding to local maxima of corner strength have been determined for all the pixels in the image the detection module 72 then (S30) determines whether the scale used for calculating smoothed images and average
- 15 second moment matrices corresponds to the final scale where  $\sigma_s = 4$ . If the scale does not correspond to the final scale the detection module 72 then selects (S32) the next largest scale for use to calculate a new smoothed image and a further set of local maxima of
- 20 normalised corner strengths (S14-S30).

In this embodiment of the present invention the scales used for setting the values of  $\sigma_s$  correspond to a set of scales where the value of  $\sigma_s$  for each scale is  
25 geometrically greater than the previous scale at a ratio of  $\sqrt{2}$ , with  $\sigma_s$  ranging between 0.5 and 4 i.e.  $\sigma_s = 0.5, 0.707, 1, 1.414, 2, 2.828$  and 4. The detection of features at a number of widely spaced scales ensures that

as far as possible different feature points are detected at each scale. In this embodiment scales greater than 4 are not used as the processing required for generating smoothed images and average second moment matrices at 5 such larger scales are relatively high and the smoothing at such large scales results in a loss of locality of feature points detected using such large scales.

When corner strengths and the co-ordinates of local maxima of corner strengths have been calculated at all of 10 the selected scales, the detection module 72 then (S34) filters the data corresponding to the local maxima detected on the basis of the normalised corner strengths for those pixels to select a required number of points 15 which have the highest corner strength and hence are most strongly indicative of corners within the images. In this embodiment, which is arranged to process image of 768 by 576 pixels, the top 400 points indicative of highest corner strengths determined at any of the seven 20 scales with  $\sigma_s$  ranging between 0.5 and 4.

When a desired number of feature points most strongly indicative of corners have determined by the detection module 72 the feature detection and characterizing module 25 2 will have stored in RAM 78 a set of coordinates for the feature points, each having an associated scale at which the feature point has been detected and the averaged second moment matrix for a region of the smoothed image

centred on the feature point. In this embodiment, the control module 70 then invokes the characterization module 74 to generate a set of data characterizing the feature point in a way which is not significantly 5 affected by viewing objects from different viewpoints as will now be described.

#### FEATURE CHARACTERIZATION

In order to characterize feature points in a way not 10 significantly effected by distortions arising from viewing objects from different view points, the characterization module 74 in this embodiment characterizes each of feature points on the basis of processed image data for a region centred on that feature 15 point, the size of which is selected utilizing information indicative of the size of a feature which has been used to select the feature point which is then converted into an image of a fixed size. This has the effect of making the characterization substantially 20 independent of the distance at which an image of an object is recorded.

The resized image data is then processed to remove 25 distortions arising from stretch and skew which result from viewing planar surfaces or surfaces which are approximately planar from different view points. The characterization module in this embodiment then generates a characterization vector utilising the processed image

data, comprising a set of values which are substantially independent of rotation of the processed image data which could arise either from rotations within the initial image data or from the processing to remove the effects  
5 of stretch and skew.

Figure 8 is a flow diagram of the processing of the characterization module 74 to characterize a feature point selected by the feature detection module 72. The  
10 processing of Figure 8 is carried out for each of the feature points detected by the feature detection module 72 so that all of the feature points are characterized in a way substantially independent of distortions resulting from viewing objects from different view points.  
15

As an initial step (S40) for characterizing a feature point, the characterization module 74 selects a portion of an image, centred on the feature point to be used as an image patch to characterize that feature point. In  
20 this embodiment of the present invention, the characterization module 74 determines the size of this image patch used to characterize a feature point on the basis of the scale at which a feature point was detected by the detection module 72. In the present embodiment,  
25 the characterization module 74 is arranged to utilize an image patch for the characterization of a feature point centred on the feature point that is twice the size of the region of an image used to detect the presence of a

feature point. In this way a feature point is characterized by an image patch which necessarily includes the entirety of the feature detected by the feature detection module 72. By characterizing a feature  
5 point using an image patch centred on the feature point which is larger than the region of an image used to detect a feature, the inclusion of some additional image data is ensured which allows for the image to be transformed to account for stretch and skew as will be  
10 described in detail later.

After the characterization module 74 has selected the size of an image patch centred on a feature point, on the basis of the scale associated with the feature which has  
15 been detected, the characterization module 74 then re-samples (S42) this image patch of the image to obtain a new image patch of fixed size. In this embodiment the size of the new image patch is set at 128 x 128 pixels. This resizing of the image patch is achieved by linear  
20 interpolation of values for pixels in the new image patch based upon the values of pixels in the original image patch. When a re-sampled image patch has been calculated this is stored in RAM 78.

25 The feature characterization module 74 then calculates a transformation required to transform the resized image patch into an image patch in which the effect of stretch and skew have been removed. The second moment matrix for

an image patch comprises values which are indicative of the rate of change of grey scale values in the image patch along the x and y coordinates. The second moment matrix for an image patch is therefore indicative of how  
5 an image patch appears to be stretched and skewed, and can therefore be utilized to determine a transformation  
to remove the distortions resulting from stretch and skew which transform squares into parallelograms and circles into ellipses as will now be described.

10

Firstly, the characterization module 74 calculates (S44) a value for the square route of an averaged second moment matrix for the current image patch. In this embodiment, since a value for the averaged second moment matrix for  
15 a feature point is calculated and stored as part of the detection of feature points by the detection module 72 for an initial iteration, this stored value for the averaged second moment matrix for a feature point on which the image is centred is utilised as the value for  
20 a calculated second moment matrix for an image patch centred on that feature point. For subsequent iterations an average second moment matrix for an image patch is calculated in the same way as has been described in relation to the calculation of second moment matrices by  
25 the detection module 72.

When either a stored value for an averaged second moment matrix has been retrieved from memory, or a value for the

average second moment matrix for an image patch has been calculated directly from the image data for an image patch the square root of this averaged second moment matrix is then determined by calculating a Cholesky 5 decomposition of the average second moment matrix. The Cholesky decomposition is the decomposition of the averaged second moment matrix M so that:

$$\begin{pmatrix} a & 0 \\ b & c \end{pmatrix} \begin{pmatrix} a & b \\ 0 & c \end{pmatrix} = \begin{bmatrix} I_x^2 & I_{xy} \\ I_{xy} & I_y^2 \end{bmatrix}$$

10 where  $a = I_x$ , and  $b$  and  $c$  are values determined by the Cholesky decomposition of the averaged second moment matrix.

The characterization module 74 then determines (S46) if 15 this calculated square root is equal to the identity matrix. If the square root of the second moment matrix for an image is equal to the identity matrix the image patch is already indicative of an image which has had the effect of stretch and skew removed and hence no further 20 transformation is required. The characterization module then proceeds to characterize such an image by calculating a set of rotational invariants (S54) as will be described later.

25 If the square root of the second moment matrix is not

equal to the identity matrix, the characterization module  
74 instead proceeds to calculate a transformed image  
corresponding to the image patch transformed by the  
square root of the second moment matrix for the image  
5 patch scaled by a scaling factor  $\lambda$  where

$$\lambda = 1/(\text{DetM})^{\frac{1}{2}}$$

In this embodiment this transformed image patch is then  
10 generated (S48) by the characterization module 74  
determining the co-ordinates of points corresponding to  
origin of pixels in a transformed image and then  
calculating (S50) pixel values on the basis of linear  
interpolation of a pixel value for these points utilising  
15 the distances and pixel values for the closest adjacent  
pixels in an original image, in a conventional manner.

Thus for example where by applying the inverse of the  
square root of the averaged second moment matrix scaled  
20 by  $1/(\det M)^{\frac{1}{2}}$  to a point corresponding to pixel at position  
 $x_1 y_1$ , the origin for that point is determined to be  $x_2 y_2$ .  
A value for the pixel at  $x_1 y_1$  in the transformed image is  
calculated by using the pixel values corresponding to the  
pixels which are closest to the point  $x_2 y_2$  in the  
25 original image to interpolate a calculated value for that  
point. A transformed image is then built up by  
calculating pixel values for each of the other points  
corresponding to pixels in the transformed image by

determining the origin for those pixels in an original image by applying the inverse square root scaled by  $1/(\det M)^{1/2}$  and then calculating pixel values by interpolating a value for a pixel in the new image from the values for pixels adjacent to the origin for that pixel using linear interpolation.

The characterising module 74 then determines (S52) whether a required number of iterations have been performed. In this embodiment the maximum number of iterations is set to be equal to two. If the required number of iterations is not equal to the maximum number of iterations which are to be performed the characterizing module 74 then proceeds to calculate the square root for the averaged second moment matrix for the transformed image patch and then generates a new transformed image utilizing this square root of the averaged second moment matrix for the image patch (S44-S52).

20

If the characterization module 74 has performed the maximum number of iterations required or it has been established that after calculating a second moment matrix for an image patch that second moment matrix is equal to identity, the transformed image patch will then correspond either exactly or approximately to an image patch from which the effects of stretch and skew have been removed. The characterization module then proceeds

to calculate a set of rotational invariants (S54) to characterize the transformed image in a manner which is substantially independent of rotation of the transformed image as will be described in detail below.

5

As stated above the second moment matrix for an image patch is indicative of the rate of change of grayscale value across an image patch. Where one image patch corresponds to another image patch which has been stretched and skewed by an affine transformation if both of these image patches are transformed by the above described process so that the second moment matrix for both of the image patches is equal to identity the transformed image patches will correspond to each other subject to an arbitrary rotation provided the second moment matrix is calculated for what amounts to identical portions of an image. This correspondence arises as is explained in "Shape-adapted Smoothing in Estimation of 3-D Shape Cues from Affine Deformations of Local 2-D Brightness Structure", Image and Vision Computing, 15 (1997) pp422-423 because of the relationship for a second moment matrix that:

$$M(BJ) = B^T M'(J) B$$

25

where  $B$  is a transformation resulting in stretch and skew of an image patch,  $M(J)$  is an averaged second moment matrix for an image patch  $J$ , and  $M'(J)$  is the second

moment matrix for an image patch  $J$  for a region of an image  $J$  which corresponds to the image patch  $BJ$ .

It then follows that if for two images  $J$  and  $J'$  which  
5 correspond to the same part of an image,  $M(J) = M(J') = I$   
and  $J' = BJ$

$$\begin{aligned} \text{then } I &= M(J') \\ &= M(BJ) \\ &= B^T M'(J) B \\ &= B^T I B \\ &= B^T B \text{ which implies } B \text{ is a rotation} \end{aligned}$$

and hence  $J$  and  $J'$  are the same image subject to an arbitrary rotation  $B$ , provided  $J$  and  $J'$  correspond to the same portions of an image (i.e.  $J' = BJ$ ).

15 In the present embodiment, the characterization module 74 is arranged to transform an image patch by a number of transformations equal to the square root of an averaged second moment matrix scaled by a scaling factor equal to  
20  $1/\det(M)^{1/2}$ . These transformations have the effect of transforming the original  $128 \times 128$  image patches used to characterize a feature point to correspond to a distorted image patch in the original image. This amounts to an approximation which is equivalent to varying of the shape  
25 of the region used for selecting an image patch so that the image patches used to characterize feature points of an object appearing in images taken from different view points correspond to the same patches of the objects

appearing in each of the images. Therefore if the second moment matrix patch for such transformed images is equal to the identity matrix, the above relationship that transformed images will correspond subject to an  
5 arbitrary rotation will hold. It has been found that good matching results occur when only one or two iterations transform an image patch and hence in this embodiment the total number of iterations is limited to two.

10

In this embodiment of the present invention after a transformed image patch for a feature point has been transformed to account for changes in scale, stretch and skew, this transformed image patch is then used to  
15 generate a characterization vector characterizing the feature point in a way substantially unaffected by distortions arising from changes of the appearance of an object by being viewed from different view points. This is achieved by generating a characterisation vector  
20 utilising calculated rotational invariants for the image patch as the combined result of processing a portion of an image to account for changes in scale, stretch skew and rotation is to characterise a point in a way substantially unaffected by distortions arising from  
25 changes of camera view point.

To achieve this the characterisation module 74 in this embodiment is arranged to generate a characterization

vector utilizing values determined using a set of masks to calculate a set of complex coefficients comprising approximate determinations of

$$U_{n,m} = \int \int F_n(r) e^{im\phi} J(r,\phi) dr d\phi$$

5 where  $J(r,\phi)$  is the transformed image centred on a feature point,  $F_n(r)$  is set of a circular symmetric functions and  $0 \leq n \leq n_{max}$ ,  $0 \leq m \leq m_{max}$ . Specifically, in this embodiment, the characterisation module is arranged to calculate a set of nine complex coefficients  
10 comprising the values for  $U_{n,m}$  for an image where  $n_{max}$  and  $m_{max}$  are equal to 2.

Under a rotation of an image:

15  $J'(r,\phi) = J(r,\phi+\theta)$

these complex coefficients undergo the following transformation:

$$U'_{n,m} = \int \int F_n(r) e^{im\phi} J'(r,\phi) dr d\phi = e^{im\theta} U_{n,m}$$

20 By calculating the above set of complex coefficients a set of values unaffected by rotation of the image may therefore be determined since

$$1) \quad \operatorname{Re}(U_{n,0}) = \operatorname{Re}(e^{\theta} U_{n,0}) \\ = \operatorname{Re}(U'_{n,0}) \text{ for } 0 \leq n \leq n_{\max} \text{ for all } \theta.$$

where  $\operatorname{Re}(z)$  is the real part of complex variable  $z$ ;

5

$$2) \quad |U_{0,m}| = |e^{im\theta} U_{0,m}| \\ = |U'_{0,m}| \text{ for } 1 \leq m \leq m_{\max} \text{ for all } \theta; \text{ and}$$

$$3) \quad U_{n,m} U'^{*}_{0,m} / |U_{0,m}| = e^{-im\theta} U_{0,m}^{*} / |U_{0,m}| \\ = U'_{n,m} U'^{*}_{0,m} / |U'_{0,m}| \text{ for } 1 \leq m \leq m_{\max} \\ 1 \leq n \leq n_{\max} \\ \text{for all } \theta.$$

where  $U^*$  is the complex conjugate of the complex variable  
15  $U$ .

Therefore the following values can be determined utilizing these complex variables which are unaffected by rotation of an image  $J(r, \phi)$ .

20

1.  $\operatorname{Re}(U_{n,0})$  for  $0 \leq n \leq n_{\max}$
2.  $|U_{0,m}|$  for  $0 \leq m \leq m_{\max}$
3.  $\operatorname{Re}(U_{n,m} U'^{*}_{0,m} / |U_{0,m}|)$  for  $1 \leq n \leq n_{\max}, 1 \leq m \leq m_{\max}$
4.  $\operatorname{Im}(U_{n,m} U'^{*}_{0,m} / |U_{0,m}|)$  for  $1 \leq n \leq n_{\max}, 1 \leq m \leq m_{\max}$

25

where

$\operatorname{Re}(z)$  is the real part of complex variable  $z$

$\operatorname{Im}(z)$  is the imaginary part of complex variable  $z$

and  $U^*$  is the complex conjugate of the complex variable  $U$ .

The calculation of approximations of:

$$5 \quad U_{n,m} = \iint F_n(r) e^{im\phi} J(r,\phi) dr d\phi$$

where  $J(r,\phi)$  is a transformed image centred on a feature point and  $F_n(r)$  is a set of a circular symmetric function with  $0 \leq n \leq 2$  and  $0 \leq m \leq 2$  in this embodiment, is approximated by the sum of scaled pixel values for a transformed image patch with each of the combinations of pixels in the transformed image scaled by a scaling mask for each pair of  $n$  and  $m$  comprising a table of scaling factors. In this embodiment, a total of eighteen scaling masks are stored in memory and then used to calculate the approximations of the real and imaginary portions of  $U_{n,m}$  with  $0 \leq n \leq 2$  and  $0 \leq m \leq 2$ . Each of these masks comprise a stored  $128 \times 128$  table of scaling factors where the scaling factors in each of the real masks correspond to calculated values for

20

$$\sigma_{n,m}^R(x,y) = F_n(r) \cos\phi$$

where  $r$  and  $\phi$  correspond to polar coordinates for a pixel at position  $x,y$  relative to the centre of an image patch and the scaling factors for each of the imaginary masks correspond to calculated values for

$$\sigma_{x,y}^I(x,y) = -F_n(r)\sin m\varphi$$

where  $r$  and  $\varphi$  correspond to polar coordinates for a  
5 pixel at a position  $x,y$  relative to the centre of an  
image patch.

Thus in this way approximation of  $U_{n,m}$  for each of the  
values of  $n,m$   $0 \leq n \leq 2$  and  $0 \leq m \leq 2$  can then be determined for  
10 a  $128 \times 128$  transformed image since

$$U_{n,m} \approx \sum_{x=0}^{128} \sum_{y=0}^{128} [\sigma_{n,m}^R(x,y) + i\sigma_{n,m}^I(x,y)]p(x,y)$$

where  $p(x,y)$  is the grey scale value of a pixel in a  
15 transformed  $128 \times 128$  image patch at position  $x,y$ .

The processing of the generation of a  
characterisation vector for a feature point by the  
characterization module 74 utilizing stored masks for  
20 calculating an approximation of  $U_{n,m}$  with

$$U_{n,m} = \iint F_n(r)e^{im\varphi} J(r,\varphi)drd\varphi$$

will now be described with reference to figures 9A, 9B  
25 and 9C which comprise a flow diagram for the calculation  
of characterization vectors utilizing a stored set of

scaling masks and corresponds to step S54 in Figure 8 and also figures 10-13 which are illustrations showing the distribution of scaling factors for scaling masks.

5 Initially (S60)  $n$  and  $m$  are set to zero. The characterization module 74 then selects (S62) from the stored set of  $128 \times 128$  masks a real mask for calculating the real value for  $U_{n,m}$ .

10 In this embodiment  $F_n(r)$  for the determination is selected to be a set of  $n$  derivatives of a Gaussian function with a standard deviation or proportional to the  $128 \times 128$  transformed image patch, with  $0 \leq n \leq 2$ . By utilising a function which decreases the further array from the 15 centre of an image patch, calculated values for  $U_{n,m}$  are most strongly dependent upon pixel values for the centre of an image patch and hence the characterization of a feature point is primarily dependent upon the portion of an image closest to the feature point.

20 Figure 10 is an illustration of the distribution of scaling factors in an example of a mask for calculating  $Re(U_{00})$  where the scaling factor for points in the image is proportional to the colour of grey in the figure.  
25 Thus for Figure 10 which illustrates to a mask for calculating an approximation of the real value of:

$$U_{00} = \iint G_\sigma(r) J(r, \varphi) dr d\varphi$$

where  $G_\sigma(r)$  is a Gaussian function with a standard deviation  $\sigma$  proportional to the size of a transformed image of 128 by 128 pixels.

5

In the case of  $U_{00}$ , since this is a completely real variable, the calculation of the real portion of the variable is the same as the calculation of the value for  $U_{00}$  itself. The mask for calculating the value of this coefficient therefore comprises a table of scaling factors, where the factors are arranged in a series of concentric circles where the scaled contribution of the image decreases exponentially from one in the centre of the image patch to zero towards the edge of the image patch in accordance with the distance of a pixel of the image patch from the centre of the image patch. Thus as illustrated in Figure 10 the small white circle at the centre of the mask corresponds to a positive scaling factor of one and the mid-grey at the edge of the mask corresponds to a scaling factor of zero.

After the mask for  $U_{00}$  has been selected a value for  $\text{Re}(U_{00})$  is calculated using the mask (S64) by summing the grey scale values of the transformed image patch, that is the image patch which has been transformed to remove the effect of stretch and skew where the contribution of each

pixel is scaled by a factor in accordance with the selected mask. In the case of  $U_{0,0}$ , this has the effect of calculating a characterization value for the image patch in a similar way for the calculation of the values for 5 pixels in the smoothed image, as the characterization value for an image patch is equal to the sum of the grey scale values for each of the pixels in the image patch where the contribution of each pixel is scaled by a scaling factor where the scaling factor decreases 10 exponentially with the distance from the centre of the image from one towards zero. The characterization module 74 then causes the calculated value to be stored in memory 78.

15 The characterization module 74 then selects (S66) an imaginary mask for calculating the imaginary portion of the complex variable under consideration. For complex variables other than  $U_{n,0}$  a value for the imaginary portion of  $U_{n,m}$  is calculated utilizing a selected mask and then 20 stored (S68).

In the case of  $U_{n,0}$  since  $U_{n,0}$  is an entirely real complex variable, the mask  $\text{Im}(U_{n,0})$  would scale all of the values for the image patch by zero. Thus in the case of  $\text{Im}(U_{n,0})$  25 the step of selecting an imaginary mask and calculating an approximation of the imaginary portion of  $U_{0,0}$  is omitted with the value zero merely being stored automatically.

The characterization module 74 then determines whether the current value of n is equal to the maximum value of m (in this embodiment 2), for which the complex variables  $U_{n,m}$  is to be calculated.

5

If the characterization module 74 determines that the current value of n is less than the maximum value of n for which the complex variables  $U_{n,m}$  are to be calculated the characterization module 74 then increments (S71) the value of n and then utilizes the new value of n to select (S62) a different mask for calculating the estimate of the real portion of another complex variable. The characterization module 74 then selects (S64) another mask for the calculation of the imaginary portion of  $U_{n,m}$  (S66) which is calculated and stored (S68). When the imaginary portions of  $U_{n,m}$  have been stored the characterization module 74 then again determines whether the current value of n is equal to the maximum value of n (S70).

20

When the characterization module 74 determines that the final value for n has been reached the characterization module then determines (S72) whether the current value of m is equal to the maximum value of m for which real and imaginary portions of  $U_{n,m}$  are to be calculated. In this embodiment the characterization module 74 checks whether m is equal to 2 as this is the greatest value of m for which  $U_{n,m}$  is calculated. If the value for m is not equal

to the maximum value of  $m$  the characterization module 74 then increments the value of  $m$  and sets the value of  $n$  to zero to calculate a further set of complex variables for each value of  $n$  from zero to  $n_{max}$  (S62-S74).

5

For each of the iterations for the calculation of values for  $U_{n,m}$  a different set of real and imaginary masks each comprising 128 by 128 tables of scaling factors is used for determining a scaling of the contributions from each 10 of the pixels in the image patch to determine the approximate value for  $U_{n,m}$ . Figures 11, 12A, 12B, 13A, 13B and 14A and 14B are illustrative examples of the arrangement of scaling factors within the 128 x 128 tables for scaling the contributions of pixels at a 15 corresponding position within the 128 x 128 image patch to calculate the values for  $U_{n,m}$  for different values of  $n$  and  $m$ .

Figure 11 is an illustrative example of the arrangement 20 of scaling factors within a 128 x 128 table for the calculation of  $U_{2,0}$ . In the case of the calculation of  $U_{2,0}$

$$U_{2,0} = \iint \frac{d^2}{dr^2} G_\sigma(r) J(r,\phi) dr d\phi$$

where  $G_\sigma(r)$  is a Gaussian function with a standard

deviation  $\sigma$  proportional to the size of the transformed image of 128 by 128 pixels.

As is the case for all of the complex variables  $U_{n,0}$  this  
5 is an entirely real variable. The imaginary portion of  
 $U_{n,0}$  is therefore equal to zero. The real portion of the  
10  $U_{2,0}$  can be determined by calculating the sum of the grey  
scale values for pixels in an image patch scaled by  
scaling factors where the scaling factors are arranged as  
shown in Figure 11.

In the case of  $U_{2,0}$  as is shown in Figure 11, the variation  
in scaling factors is illustrated by varying shades of  
grey where white corresponds to a positive scaling factor  
15 of 1, black corresponds to the negative scaling factor of  
-1 and the mid grey at the edge of the figure corresponds  
to a value of zero. In the case of a mask for  
calculating the value of  $\text{Re}(U_{2,0})$  the scaling factors vary  
between -1 and 1. The scaling mask is such that the  
20 central portion of an image patch being scaled by a  
factor of -1, with an annulus further away from the  
centre of the image having a scaling factor of 1, with  
the scaling factor varying from -1 to 1 gradually as it  
moves away from the centre towards this annulus. Beyond  
25 this annulus the scaling factor reduces from 1 to 0  
further away from the centre of the image patch.

Figures 12A and 12B are exemplary illustrations of

arrangements of scaling factors within tables for masks for calculating the real and imaginary portions of  $U_{0,1}$  respectively. As in the case of Figures 10 and 11 these scaling factors are shown proportionately as shade of grey in the Figure where black indicates a scaling factor of -1, white indicates a scaling factor of 1 and a mid grey at the edge of the figure indicates a scaling factor of zero with intermediate shades of grey being indicative of intermediate scaling factors.

10

In the case of the real portion of  $U_{0,1}$  as is shown in Figure 12A, the scaling mask comprises two regions, one on the left hand side of the image patch where the contributions of pixels on that side of the image patch are scaled by negative scaling factors and a symmetrical region in the right hand side of the image patch where the contributions of pixels in that region of the image patch are scaled by a positive scaling factors proportional to the corresponding negative scaling factors of pixels in the left hand portion of the image.

Figure 12B is an illustration of arrangements of scaling factors within a table for a mask for calculating the imaginary portion of  $U_{0,1}$ . The mask of figure 12B is identical to the mask of Figure 12A except that the mask is rotated about the centre of the image patch by  $90^\circ$  so that a region of the image patch at the top of the patch

is scaled by a variety of negative scaling factors and a symmetrical region of the image patch at the lower portion of the image is scaled by positive scaling factors.

5

Figures 13A and 13B are illustrative examples of arrangements of scaling factors within tables for masks for calculating the real and imaginary portions of  $U_{0,2}$ . The masks indicate the scaling factors for different portions of an image in the same manner as Figures 10, 11, 12A and 12B with white indicating a positive scaling factor of 1, black indicating a negative scaling factor of -1 and intermediate shades of grey indicating intermediate scaling factors with the mid grey at the edge of the figure indicating a scaling factor of zero.

As can be seen from Figure 13A the mask for the scaling of contributions of an image to determine the value for the real part of  $U_{0,2}$  comprises a pair of regions aligned along an axis running from the top left hand corner of an image patch to the bottom right hand corner of the image patch which scale the contributions of pixels in an image patch by positive factors and a pair of regions along an axis from the top right hand corner of the figure to the bottom left hand corner of the figure composing two regions in which the patch are scaled by negative scaling factors.

The scaling mask of figure 13B for determining the imaginary portion of  $U_{0,2}$  comprises a similar arrangement of similar regions to that of Figure 13A in which the regions are arranged along axes rotated 45° anti clockwise  
5 relative to the orientations of the same regions in the mask for calculating the real portion of  $U_{0,2}$  shown in Figure 13A.

When the characterization module 74 has calculated all of  
10 the required values of  $U_{n,m}$  data representative of these values will be stored in memory 78. The characterization module 74 then proceeds to utilize these values to generate sequentially a characterization vector characterizing the sampled image patch as will now be  
15 described.

In order to generate the characterization vector for a feature point the characterization module 74 initially sets the value of n to zero (S78).  $U_{0,0}$  which is an  
20 entirely real variable is then stored (S80) in memory 78 as part of the characterization vector for the feature point for which the values of  $U_{n,m}$  have been determined. The characterization module 74 then determines (S82) whether n is equal to  $n_{max}$  i.e. in this embodiment whether  
25 n = 2. If this is not the case the characterization module increments n (S84) and stores the value of  $U_{n,0}$  for the new value of n as the next value in the sequentially generated characterization vector for the feature point

(S80). In this way all of the values of  $U_{n,0}$  for  $0 \leq n \leq n_{\max}$  are stored as part of the characterization vector for a feature point.

5 When the characterization module 74 determines (S82) that  $n = n_{\max}$ , the characterization module then sets  $n$  and  $m$  equal to 1 (S86). The characterization module 74 then determines (S88) and stores in the memory 78 the value of the modulus of  $U_{0,m}$  as the next value of the sequentially generated characterization vector for the feature point currently being processed, with the modulus of  $U_{0,m}$  being determined from the value for the real and imaginary portions of  $U_{0,m}$  stored in memory 78.

10 The characterization module 74 then determines (S90) a value for the complex conjugate of  $U_{0,n}$  from the values for  $U_{0,m}$  stored in memory 78 and determines from the values for the complex conjugate  $U_{0,m}^*$  the value for

15 
$$U_{0,m}^*/|U_{0,m}|$$

where  $U_{0,m}^*$  is the complex conjugate of  $U_{0,m}$  and  $|U_{0,m}|$  is the modulus of  $U_{0,m}$ .

20 The characterization module 74 then determines (S92) and stores the real and imaginary portions of the product of  $U_{n,m}$  and  $U_{0,m}^*/|U_{0,m}|$  with the real and imaginary portions of this product being stored as parts of the sequentially

generated characterization vector for the feature point being processed.

The characterization module 74 then determines (S94) whether the current value for n is equal to  $n_{max}$  (i.e. in this embodiment does  $n = 2$ ). If this is not the case the characterization module 74 then increments n (S96) and calculates a further set of values for the real and imaginary portions of the product of  $U_{n,m}$  and  $U^*_{0,m}/|U_{0,m}|$  utilizing this new value of n. In this way the product of  $U_{n,m}$  and  $U^*_{0,m}/|U_{0,m}|$  for all values of n are calculated and stored as part of the sequentially generated characterization vector for a feature point.

When the characterization module 74 establishes that  $n = n_{max}$  the characterization module then (S98) tests to determine whether m is  $m_{max}$ . In this embodiment this means the characterization module 74 tests to determine whether  $m = 2$ . If m is not equal to  $m_{max}$  the characterization module 74 increments m (S100) and resets n to 1 and then proceeds to calculate and store as parts of the characterization vector for a feature point a modulus of  $U_{0,m}$  utilizing the new m and the products of  $U^*_{0,m}/|U_{0,m}|$  and  $U_{n,m}$  with  $1 \leq n \leq n_{max}$  (S88-S96). In this way the characterization module generates a characterization vector utilizing the values for  $U_{n,m}$  in a way which generates values which are substantially independent of rotation of images in the transformed image patch.

Thus for example in the present embodiment where  $m_{max}$  and  $m_{max}$  are both equal to 2 the generated characterization vector comprises the following thirteen values:

5

$$U_{0,0}, U_{1,0}, U_{2,0} |U_{0,1}|, \operatorname{Re}(U_{1,1}V_{0,1})$$

$$\operatorname{Im}(U_{1,1}V_{0,1}), \operatorname{Re}(V_2, V_{0,1}), \operatorname{Im}(U_2, V_{0,1})$$

$$|U_{0,2}|, \operatorname{Re}(U_{1,2}V_{0,2}), \operatorname{Im}(U_{1,2}V_{0,2}),$$

$$\operatorname{Re}(U_{2,2}V_{0,2}), \operatorname{Im}(U_{2,2}V_{0,2})$$

10 where  $V_{0,1} = U_{0,1}^*/|U_{0,1}|$  and

$$V_{0,2} = U_{0,2}^*/|U_{0,2}|$$

all of which are substantially independent of rotation of a transformed image patch.

15 As the selection and processing of an image patch for the characterization of a feature point generates an image patch for a feature point which is substantially independent of distortions arising from changes in scale and distortions of stretch and skew arising from changes  
20 of view point, the combined result of selecting an image patch, processing the patch and characterizing a transformed image patch in a way which is substantially independent of rotation, is to generate a characterization vector for a feature point which is substantially independent of distortions arising from changes of camera view point.  
25

MATCHING MODULE

When all the feature points of a pair of images have had characterization vectors generated for them in the manner described above the control module 70 then invokes the 5 matching module 76 to determine which feature points in one image are most likely to correspond to the feature points in the second image, utilising these characterization vectors. As the characterization vectors for feature points are substantially independent 10 of distortions arising from changes of camera view point the matching of feature points between pairs of images should result in the matching of points corresponding to the same physical point on an object in a pair of images of that object taken from different view points.

15

Figure 14 is a flow diagram of the processing of the matching module 76. Initially (S110) in order to remove systematic correlations between the characterization vectors for the feature points, a covariance matrix for 20 the characterization vectors is calculated in a conventional manner. New characterization vectors are then calculated for the feature points in the images where the new characterization vectors for feature points are determined from the previously calculated 25 characterization vectors which are multiplied by the square root of the covariance matrix for the characterization vectors. All of these new characterization vectors are then stored in memory 78.

The calculation of the new set of characterization vectors has the effect of generating a set of normalised characterization vectors, normalised to remove systematic correlations between the values of the vector which arise  
5 because of systematic correlations within the original image data.

The matching module 76 then (S112) determines how closely normalised characterization vectors for points in one  
10 image correspond to characterization vectors for points in another image. The correspondence between vectors is determined by calculating the square of the Euclidean distances between each of the normalised characterization vectors for features points in one image to each of the  
15 normalised characterisation vectors for points in the other image. These squares of Euclidean distances are indicative of the square of Mahalanobis distances between the characterization vectors originally calculated by the characterization module 74 for feature points in the  
20 images, since the Mahalanobis distance between two vectors  $x_i x_j$  is defined by:

$$d(x^i, x^j) = \sqrt{((x^i - x^j)^T C^{-1} (x^i - x^j))}$$

25 where C is the covariance matrix for the data.

The matching module 78 then determines (S114) for each of the normalised characterization vectors of feature points

The ambiguity score calculated by determining a ratio between the most closely corresponding and second most closely corresponding normalised characterization vectors for points in the second image is indicative of the 5 ambiguity of the best match for the point in the first image to a point in the second image. Where the ambiguity score is significantly less than one this indicates that the best candidate match for a point in the second image for matching to a point in the first 10 image is characterized in a way in which it is clearly closer to the characterization of the feature point in the first image than any other point in the second image. Where the ambiguity score is close to one this indicates that there are alternative matches for a feature point in 15 the first image whose characterization vectors are almost as good as a match as the feature point which most closely matches the characterization vector of the feature point in the first image.

20 By selecting the matches for pairs of images on the basis of selecting the least ambiguous matches the points which are matched are least likely to be incorrectly matched.

Thus for example in Figure 2A portions of images about 25 points in the first image 20 corresponding to windows 24,26,28,30 are very similar and hence characterization vectors generated for these points would also be very similar. After a transformation resulting from a change

error is substantial. Thus where a large number of equally likely candidates for a matching exist it is preferable to ignore that potential match, regardless of how strong it might be.

5

Thus in this embodiment, when ambiguity scores have been determined for the potential matches for each of the points in the first image the matching module 76 then selects (S118) from the list of matches the matches which have the lowest ambiguity scores. Selecting the matches having the lowest ambiguity scores ensures that matches which are selected are most likely to correspond to unique portions of images and hence are most likely to correspond to the same point on an object in images of an object taken from different view points. The matching module 76 then outputs (S120) a list comprising pairs of coordinates for the points in the first image having the lowest ambiguity scores and the corresponding points in the second image whose characterization vectors most closely correspond to those points. This list of coordinates being those points in the images which correspond to the same physical points on an object appearing in those images. This list of matched feature points is then output to the output buffer 62 and is then made available for example by being sent to the camera position calculation module 6 in the form of an electrical signal or by being output on a disc for further processing by the camera position calculation

in an image then proceeds utilizing this grey scale image in the manner previously described. Thus in this way the points within the colour image corresponding to corners is determined.

5

The characterization module 74, in this embodiment is arranged to select and transform image patches of the colour image associated with feature points in the same way as is described in relation to the first embodiment 10 to establish transformed colour images associated with feature points which are transformed to account for the effect of stretch and skew.

However, in contrast to this previous embodiment, the 15 characterization module 74 is then arranged to determine a set of complex coefficients utilizing scaling masks as has previously been described to obtain scaled sums of each of the individual red, green and blue components of the pixels for the transformed image patches. This is 20 achieved in the same manner as has been described in relation to the calculation of complex coefficients for a grey scale image with each of the red, green and blue channels being treated as a separate grey scale image. The characterization module 74 then calculates the 25 following values for an image patch which are independent of the rotation of image data for that image patch:

$$\operatorname{Re}(U_{n,0}^R) \quad 0 \leq n \leq n_{\max}$$

$$\operatorname{Re}(U_{n,0}^G) \quad 0 \leq n \leq n_{\max}$$

minimised. These errors arise because the values for the complex coefficients are calculated by approximation of integrations by calculations of scaled sums. Since only the argument of some complex variables are used to account for variations arising due to rotation, the most reliable complex variable to use will have the largest modulus, as the argument for this complex coefficient will be least effected by small variations in the values of the calculated values for its real and imaginary parts arising due to approximations.

When all of these values for the characterization of an image patch have been determined the matching module 76 then utilizes characterization vectors including all of these values for matching one point in an image to its best match in a second image. Thus in this way the additional data available in a colour image can be used to increase the data which can be used to match points in different images.

20

#### THIRD EMBODIMENT

Although in the previous embodiments the present invention has been described in the context of a feature detection and characterization module 2 for a system for generating three-dimensional computer models from images taken from different viewpoints, the present invention may also be used in a number of other ways. In this embodiment of the present invention the detection and

characterizations for index images stored in the database 300. The matching module 76 then determines which of the stored images best matches the input image by selecting the image having the greatest number of unambiguous  
5 matches.

Thus in this way the matching module 76 determines which of the images having characterisation values stored in the database 300 most closely corresponds to the image received in the image buffer by determining the best matches between characterized feature points for an image in the image buffer and each of the images in the database and then on the basis of those matches determining which of the images in the database 300 most  
10 closely corresponds to the image in the image buffer 60.  
15 The CPU 64 then retrieves a copy of the image in the database 300 and outputs the retrieved image for comparison with the input image. Thus by characterising the image received by the image buffer 60 in the way  
20 previously described a similar image stored in the databases 300 may be retrieved and output from a database.

#### FOURTH EMBODIMENT

25 In the processing of the previous embodiment an input image was characterised and the characterisation of the image was then compared to a database of images each of which had previously been characterised to retrieve from

stored values for an original image therefore identifies whether an image input into the image buffer 60 is a copy of an earlier image whose characterisation is stored in the database 300. In particular, by deliberately 5 introducing certain features into an image which will result in the output of certain predefined characterization values following the analysis of the image by a feature detection and characterization module, a means is provided which enables the identification of 10 the origin of subsequent copies of those images.

FIFTH EMBODIMENT

In the previous embodiment the present invention has been described in terms of apparatus for identifying and 15 characterizing feature points matching those feature points with similarly characterized feature points either in other images or against a database of previously characterized images. In this embodiment of the present invention apparatus is provided which is arranged to 20 remove the effects of stretch and skew from an image and to output an image transformed to account for the effect of stretch and skew.

Figure 16 is a block diagram of apparatus in accordance 25 with the fifth embodiment of the present invention. The apparatus in accordance with this embodiment of the present invention is identical to the feature detection and matching module 2 of the first embodiment except that

the output buffer 62.

In this way by transforming an image in the image buffer 60 by a number of iterations utilizing the square root of 5 a calculated second moment matrix for the image an output image is generated which corresponds to the original image transformed to a skew normalised frame. In this way a number of images taken from different view points which introduce a skew into an image can be transformed 10 to images where this skew is removed so that the different images with the skew removed may be compared.

FURTHER AMENDMENTS AND MODIFICATIONS

15 In the previous embodiments the detection module 72 has been described which is arranged to identify feature points in images corresponding to corners on objects in the images. However, the detection module 72 could be arranged to detect alternative features. Thus for 20 example instead of calculating normalised corner strengths (where a value representative of a strength of a corner is determined and scaled in accordance with the size of the portion of an image used to detect a corner strength), other values representative of some features 25 in an image with these values being scaled to account for the variation in such values arising due to the size of the region. Suitable features which might be detected could include points indicative of high curvature such as

feature points of interest. The detection of feature points using larger windows larger than 14 by 14 for this size of image has not been found to improve the ability of a feature detection and matching module 2 to match 5 features more accurately. This is due to the increased computational complexity required for calculating smoothed values over such a large region and the fact that the determination of a feature point utilizing such a large region is not sufficiently specific to enable a 10 detected feature point to be accurately matched with other points in other images.

In the detection module 72 described above the selection of feature points for subsequent processing is described 15 in terms of selecting a desired number of feature points. However, the normalised feature strength determined by the detection module 72 could itself be used to filter a list of potential feature points with only those feature points having a normalised feature strength greater than 20 a set threshold being utilized in subsequent processing. The advantage of utilizing a threshold to select those features which are selected for future processing is that this ensures only those features having particularly strong feature detection values are subsequently 25 processed.

In the previous embodiments the characterization module 74 has been described arranged to characterize a feature

In the case of such rotational invariants a suitably shaped image patch to characterize a point utilizing rotational invariants would be a circular image patch. By making the shape of a selected image patch dependent upon the manner in which an image patch is to be characterized, a means is provided to ensure that a feature point is characterized in to generate characterization values invariant for distortions for which characterization values are calculated. The size of this image patch could then be arranged to be selected on the basis of a scale associated with a detected feature point.

Although in the above described embodiments one way of associating a scale with a feature point has been described where the strength of the feature point is reduced proportionately to account for the different sizes of regions utilized to detect the feature point, other ways associating a detected feature point for this scale could be used. Thus for example where features are detected at a number of different scales a 'scale space' maximum could be determined in a manner suggested by Lindeberg in 'Scale Space Theory in Computers', Kluwer Academic, Dordrecht, Netherlands, 1994. This suggests that by detecting the strength of feature points across a range of scales, a scale which associates a point most strongly with a calculated feature strength can be determined. The scale associated with such "scale space

④ ⑤

In the embodiments above the processing performed is described in terms of a CPU using processing defined by programming instructions. However, some or all, of the processing could be performed using hardware.

⑥

### 1.2.2 Calculate edge strengths and directions

The edge strengths and directions are calculated using the 7x7 integrated directional derivative gradient operator discussed in section 8.9 of Haralick and Shapiro<sup>i</sup>.

The row and column forms of the derivative operator are both applied to each pixel in the grey scale image. The results are combined in the standard way to calculate the edge strength and edge direction at each pixel.

The output of this part of the algorithm is a complete derivative image.

15

### 1.2.3 Calculate edge boundaries

The edge boundaries are calculated by using a zero crossing edge detection method based on a set of 5x5 kernels describing a bivariate cubic fit to the neighbourhood of each pixel.

The edge boundary detection method places an edge at all pixels which are close to a negatively sloped zero crossing of the second directional derivative taken in the direction of the gradient, where the derivatives are defined using the bivariate cubic fit to the grey level surface. The subpixel location of the zero crossing is also stored along with the pixel location.

30

The method of edge boundary detection is described in more detail in section 8.8.4 of Haralick and Shapiro<sup>i</sup>.

correlation based matcher to make the measurements of corner correspondences.

The method assumes that the motion of corners is smooth  
5 enough across the sequence of input images that a constant velocity Kalman filter is useful, and that corner measurements and motion can be modelled by gaussians.

10    2.2 Algorithm

- 1)    Input corners from an image.
- 2)    Predict forward using Kalman filter.
- 15    3)    If the position uncertainty of the predicted corner is greater than a threshold,  $\Delta$ , as measured by the state positional variance, drop the corner from the list of currently tracked corners.
- 20    4)    Input a new image from the sequence.
- 5)    For each of the currently tracked corners:
  - 25    a)    search a window in the new image for pixels which match the corner;
  - b)    update the corresponding Kalman filter, using any new observations (i.e. matches).
- 30    6)    Input the corners from the new image as new points to be tracked (first, filtering them to remove any which are too close to existing tracked points).

This uses the positional uncertainty (given by the top two diagonal elements of the state covariance matrix, K) to define a region in which to search for new measurements (i.e. a range gate).

5

The range gate is a rectangular region of dimensions:

$$\Delta x = \sqrt{K_{11}}, \Delta y = \sqrt{K_{22}} \quad \dots A-6$$

10

The correlation score between a window around the previously measured corner and each of the pixels in the range gate is calculated.

15 The two top correlation scores are kept.

If the top correlation score is larger than a threshold,  $C_0$ , and the difference between the two top correlation scores is larger than a threshold,  $\Delta C$ , then the pixel  
20 with the top correlation score is kept as the latest measurement.

### 2.2.3 Update

25 The measurement is used to update the Kalman filter in the standard way:

$$G = KH^T (HKH^T + R)^{-1} \quad \dots A-7$$

$$X \leftarrow X + G(\hat{X} - HX) \quad \dots A-8$$

$$K \leftarrow (I - GH)K \quad \dots A-9$$

The algorithm's behaviour over a long sequence is anyway not too dependent on the initial conditions.

5 The process velocity variance is set to the fixed value of 50 (pixels/frame)<sup>2</sup>. The process velocity variance would have to be increased above this for a hand-held sequence. In fact it is straightforward to obtain a reasonable value for the process velocity variance adaptively.

10

The measurement variance is obtained from the following model:

$$\sigma^2 = (rK+a) \quad \dots\text{A-13}$$

15 where  $K = \sqrt{(K_{11}K_{22})}$  is a measure of the positional uncertainty, "r" is a parameter related to the likelihood of obtaining an outlier, and "a" is a parameter related to the measurement uncertainty of inliers. "r" and "a" are set to r=0.1 and a=1.0.

20 This model takes into account, in a heuristic way, the fact that it is more likely that an outlier will be obtained if the range gate is large.

25 The measurement variance (in fact the full measurement covariance matrix R) could also be obtained from the behaviour of the auto-correlation in the neighbourhood of the measurement. However this would not take into account the likelihood of obtaining an outlier.

30 The remaining parameters are set to the values:  $\Delta=400$  pixels<sup>2</sup>,  $C_0=0.9$  and  $\Delta C=0.001$ .

process.

- Finally the triangulation is textured, using appropriate parts of the original images to provide  
5 the texturing on the triangles.

### 3.2 Segmentation

The aim of this process is to segment an object (in front  
10 of a reasonably homogeneous coloured background) in an image using colour information. The resulting binary image is used in voxel carving.

Two alternative methods are used:

15 Method 1: input a single RGB colour value representing the background colour - each RGB pixel in the image is examined and if the Euclidean distance to the background colour (in RGB space) is  
20 less than a specified threshold the pixel is labelled as background (BLACK).

Method 2: input a "blue" image containing a representative region of the background.

25 The algorithm has two stages:

- (1) Build a hash table of quantised background colours
- 30 (2) Use the table to segment each image.

Step 1) Build hash table

## Step 2) Segment each image

Go through each RGB pixel, "v", in each image.

5 Set "w" to be the quantised version of "v" as before.

To decide whether "w" is in the hash table, explicitly look at all the entries in the bin with index  $h(w)$  and see if any of them are the same as "w". If yes, then "v" is a background pixel - set the corresponding pixel in the output image to BLACK. If no then "v" is a foreground pixel - set the corresponding pixel in the output image to WHITE.

10 15 Post processing: for both methods a post process is performed to fill small holes and remove small isolated regions.

A median filter is used with a circular window. (A circular window is chosen to avoid biasing the result in the x or y directions.)

20 Build a circular mask of radius "r". Explicitly store the start and end values for each scan line on the circle.

25 Go through each pixel in the binary image.

Place the centre of the mask on the current pixel. Count 30 the number of BLACK pixels and the number of WHITE pixels in the circular region.

If ( $\#WHITE$  pixels  $\geq$   $\#BLACK$  pixels) then set corresponding

Voxel carving is described further in "Rapid Octree Construction from Image Sequences" by R. Szeliski in CVGIP: Image Understanding, Volume 58, Number 1, July 1993, pages 23-32.

5

### 3.4 Marching cubes

The aim of the process is to produce a surface triangulation from a set of samples of an implicit function representing the surface (for instance a signed distance function). In the case where the implicit function has been obtained from a voxel carve, the implicit function takes the value -1 for samples which are inside the object and +1 for samples which are outside the object.

Marching cubes is an algorithm that takes a set of samples of an implicit surface (e.g. a signed distance function) sampled at regular intervals on a voxel grid, and extracts a triangulated surface mesh. Lorensen and Cline<sup>iii</sup> and Bloomentahl<sup>iv</sup> give details on the algorithm and its implementation.

The marching-cubes algorithm constructs a surface mesh by "marching" around the cubes while following the zero crossings of the implicit surface  $f(x)=0$ , adding to the triangulation as it goes. The signed distance allows the marching-cubes algorithm to interpolate the location of the surface with higher accuracy than the resolution of the volume grid. The marching cubes algorithm can be used as a continuation method (i.e. it finds an initial surface point and extends the surface from this point).

*plane of each triangle*  
*If (distance < threshold)*  
*Discard V and keep new triangulation*  
*Else*  
*Keep V and return to old triangulation*

5

*OUTPUT*

*Output list of kept vertices*  
*Output updated list of triangles*

10

The process therefore combines adjacent triangles in the model produced by the marching cubes algorithm, if this can be done without introducing large errors into the model.

15

The selection of the vertices is carried out in a random order in order to avoid the effect of gradually eroding a large part of the surface by consecutively removing neighbouring vertices.

20

### 3.6 Further Surface Generation Techniques

25 Further techniques which may be employed to generate a 3D computer model of an object surface include voxel colouring, for example as described in "Photorealistic Scene Reconstruction by Voxel Coloring" by Seitz and Dyer in Proc. Conf. Computer Vision and Pattern Recognition  
 30 1997, p1067-1073, "Plenoptic Image Editing" by Seitz and Kutulakos in Proc. 6th International Conference on Computer Vision, pp 17-24, "What Do N Photographs Tell Us About 3D Shape?" by Kutulakos and Seitz in University of

appear to be much of a problem.

It has been found that, if every image is used for  
texturing then this can result in very large VRML models  
5 being produced. These can be cumbersome to load and  
render in real time. Therefore, in practice, a subset of  
images is used to texture the model. This subset may be  
specified in a configuration file.

10

References

i R M Haralick and L G Shapiro: "Computer and Robot Vision Volume 1", Addison-Wesley, 1992, ISBN 0-201-10877-1 (v.1), section 8.  
15

ii J Foley, A van Dam, S Feiner and J Hughes: "Computer Graphics: Principles and Practice", Addison-Wesley, ISBN 0-201-12110-7.

20 iii W.E. Lorensen and H.E. Cline: "Marching Cubes: A High Resolution 3D Surface Construction Algorithm", in Computer Graphics, SIGGRAPH 87 proceedings, 21: 163-169, July 1987.

25 iv J. Bloomenthal: "An Implicit Surface Polygonizer", Graphics Gems IV, AP Professional, 1994, ISBN 0123361559, pp 324-350.

said characterization means is arranged to determine the shape of a region to be used to generate characterization data for a feature on the basis of values of image data for a region of said image including said feature so that  
5 said characterization is substantially unaffected by transformations resulting in linear distortions of said region of said image.

4. Apparatus in accordance with claim 1, wherein said  
10 characterisation means comprises:

means for determining the rate of change of luminance along two axes for a said region of said image;  
means for determining a transformed image utilizing said rates of change of luminance; and  
15 means for generating characterization data characterizing a said region of said image utilizing said transformed image.

5. Apparatus in accordance with claim 3 or claim 4,  
20 wherein said characterization means comprises:

means for determining for a said region an averaged second moment matrix for a feature, wherein said averaged second moment matrix comprises a scaled sum of second moment matrices for each pixel in said region, and said 25 second moment matrices for each of said pixels comprises:

factor.

7. Apparatus in accordance with claim 6, wherein said scaling factor is inversely proportional to the square root of the determinant of the averaged second moment matrix for a said region.

8. Apparatus in accordance with claim 7, wherein said transformation means is arranged to iteratively generate transformed image data for a said region of said image until the calculated second moment matrix for said transformed image is equal to identity, and wherein said characterisation means is arranged to characterize said feature on the basis of said iteratively transformed image data.

9. Apparatus in accordance with any preceding claim further comprising matching means for identifying matches between features in pairs of images, wherein said matching means is arranged to determine a match between features in pairs of images on the basis of characterization by said characterization means of features in said pair of images.

25 10. Apparatus in accordance with claim 8, further

input means for receiving image data;  
transformation calculating means for determining a transformation to remove affine distortions from image data received by said input means; and

5       transformed image generation means for generating transformed image data corresponding to image data received by said input means transformed by said transformation determined by said transformation determination means;

10      wherein said transformation calculating means is arranged to determine the transformation to remove the effects of affine distortions from the received image data by determining a transformation such that the second moment matrix for said image transformed by said transformation is substantially equal to the identity matrix.

13. Apparatus in accordance with claim 12, wherein said transformation calculating means is arranged to determine  
20      said transformation by determining the square root of a second moment matrix for image data received by said input means.

14. Apparatus in accordance with claim 13, wherein said  
25      transformation calculating means is arranged to calculate

determination means determines that the second moment matrix for said transformed image is not substantially equal to identity.

5       17. Apparatus in accordance with claim 16, wherein said second moment determination means is arranged to determine the rate of change of luminance along two axes for a transformed matrix and to determine the second moment matrix for a transformed image utilizing said 10 rates of change of luminance.

18. A method for generating characterization data characterizing an image comprising the steps of:  
receiving image data representative of an image;  
15       detecting a plurality of features in said image; and  
generating characterization data, characterising said features, by generating data characterising portions of said image data representative of regions of images including said features, wherein said generation step is  
20       such that said characterization data generated is substantially unaffected by transformations resulting in linear distortions of said regions including said features.

25       19. A method in accordance with claim 18, wherein said

said characterization step comprises the steps of:

determining for a said region of an image including  
a feature an averaged second moment matrix for said  
feature, wherein said averaged second moment matrix  
5 comprises a scaled sum of second moment matrices for each  
pixel in said region, and said second moment matrices for  
each of said pixels comprises:

$$M = \begin{pmatrix} I_x^2 & I_x I_y \\ I_x I_y & I_y^2 \end{pmatrix}$$

where  $I_x$  and  $I_y$  are values indicative of the rate of  
10 change of luminance of an image along two different axes;  
and

determining for said region of said image including  
said feature a transformed image transformed to account  
for distortions arising from sketch and skew on the basis  
15 of said second moment matrix determined for said region;  
and

calculating characterisation values for a feature on  
the basis of the calculation of rotational invariants  
determined for said transformed image.

20

23. A method in accordance with claim 22, wherein the  
determination of a transformed image comprises

transformed image data for a said region of said image until the calculated second moment matrix for said transformed image is substantially equal to identity, and said characterization comprises means characterizing said 5 feature on the basis of said iteratively transformed image data.

27. A method of identifying correspondences between features in pairs of images, comprising the steps of:

10 generating characterization data for images in accordance with any of claims 18 to 26; and determining a match between features in pairs of images utilizing said characterization data.

15 28. A method in accordance with claim 27 further comprising the step of generating a signal conveying information defining said correspondences.

20 29. A method in accordance with claim 28, further comprising the step of recording said generated signal on a recording medium either directly or indirectly.

30. A method for generating a three-dimensional model from images of objects comprising the steps of:  
25 identifying the correspondence between features in

image data on the basis of the interpolation of values  
for image data representative of the origins of pixels in  
the transformed image transformed by the inverse square  
root of a second moment matrix determined for said image  
5 stored in said storage means multiplied by a scaling  
factor inversely proportional to the square root of the  
determinant of said second moment matrix.

33. A method in accordance with claim 32, further  
10 comprising the steps of determining a second moment  
matrix for a transformed image and generating further  
transformed image data from said transformed image data,  
if the second moment for said transformed image is not  
substantially equal to identity.

15

34. A method in accordance with claim 33, wherein said  
second moment matrix for a transformed image is  
determined by the steps of:

determining the rate of luminance along two axes for  
20 a said transformed image, and determining said second  
moment matrix utilizing said rates of change of  
luminance.

35. In an apparatus for generating a three-dimensional  
25 computer model of an object by processing images of the

images comprising:

storing image data;

detecting the presence of features in the images represented by stored image data,

5 generating characterization data for said features in the images in a manner substantially unaffected by linear distortions of regions of said images including a said feature; and

matching features in different images utilizing said 10 generated characterization data.

37. In a method for generating a three-dimensional computer model of an object by processing images of the object taken from a plurality of different viewpoints to 15 match features in the images, calculating the viewpoints at which the images were recorded using the matched features, and generating a three-dimensional computer model of the surface object using the calculated viewpoints, an improvement comprising matching features 20 in the images by:

storing image data;

detecting the presence of features in the images represented by stored image data,

generating characterization data for said features 25 in the images in a manner substantially unaffected by

## ABSTRACT

IMAGE PROCESSING METHOD AND APPARATUS

An apparatus (2) for matching features in images of objects taken from different viewpoints is provided comprising: an image buffer (60) for receiving image data; and output buffer (62) for outputting pairs of matched features and processing means (64-78) for processing received image data to determine matched pairs of features in images. The processing means (64-78) includes a detection module (72) for detecting features at a number of different scales to account for the possibility that a feature in one image may correspond to a larger or smaller feature in another image; a characterization module (74) for generating characterization data for selected features where the characterization data is substantially independent of changes of scale, and the effects of stretch and skew resulting from viewing objects from different viewpoints; and a matching module (76) for outputting as pairs of matched features, features which most closely correspond to each other which are unambiguously better matches than any alternative match between features in different images.

Refer to Figure 5

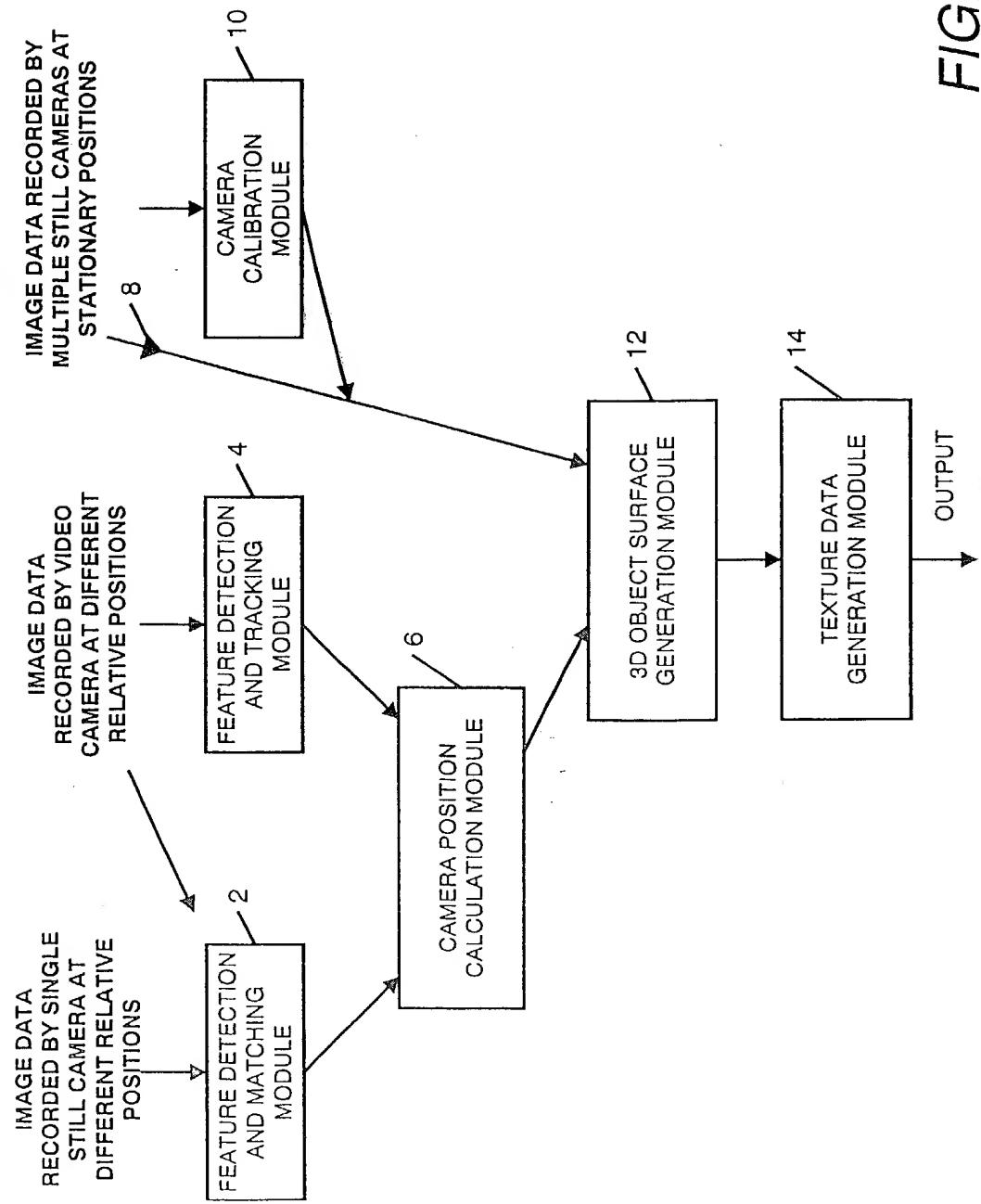


FIG.2A

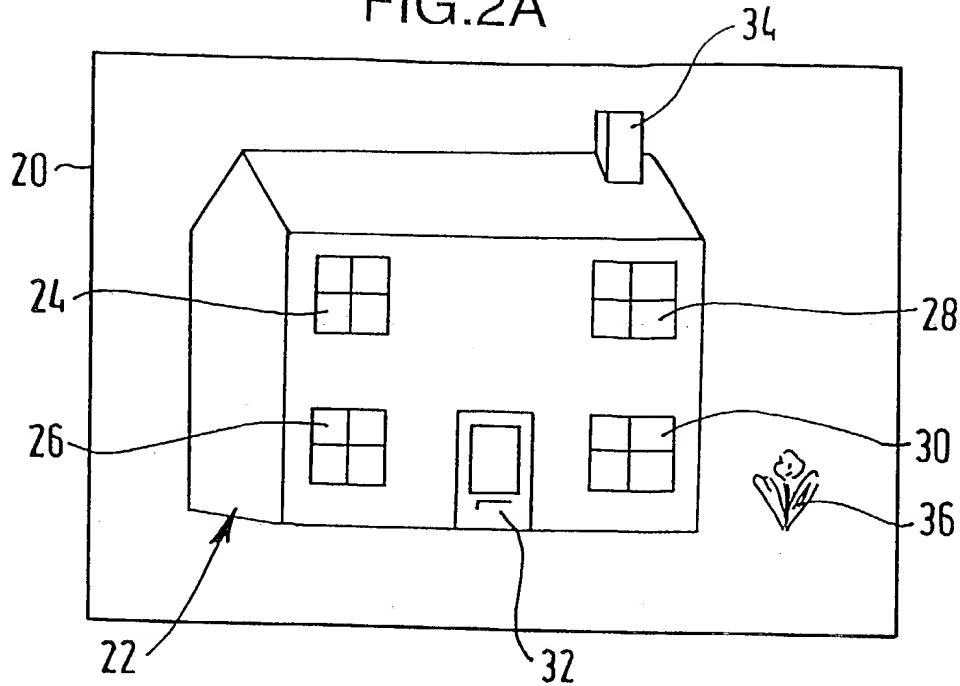


FIG.2B

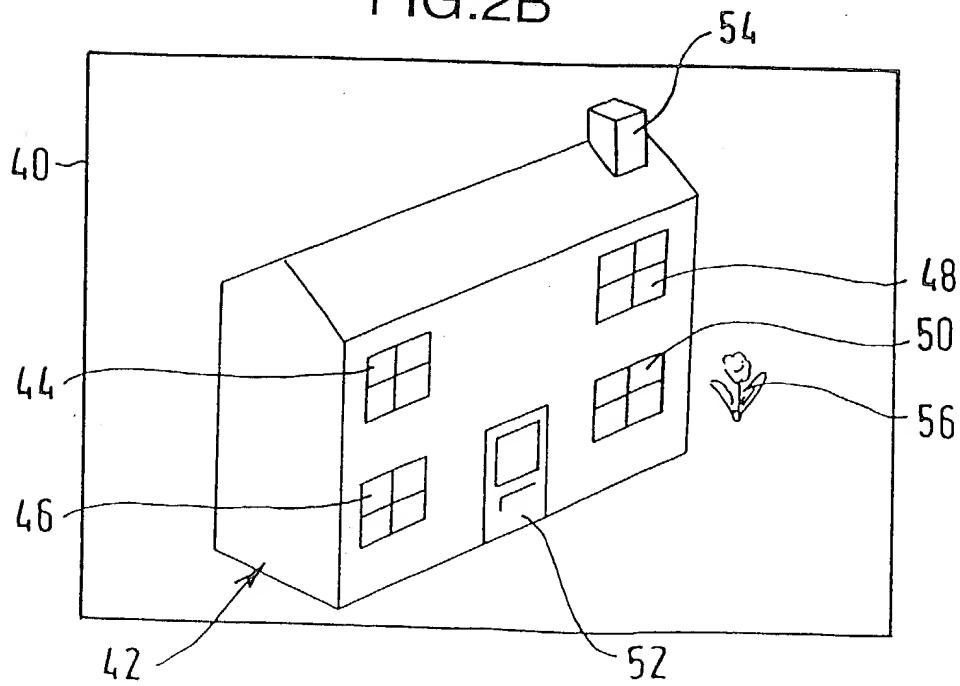


FIG.3

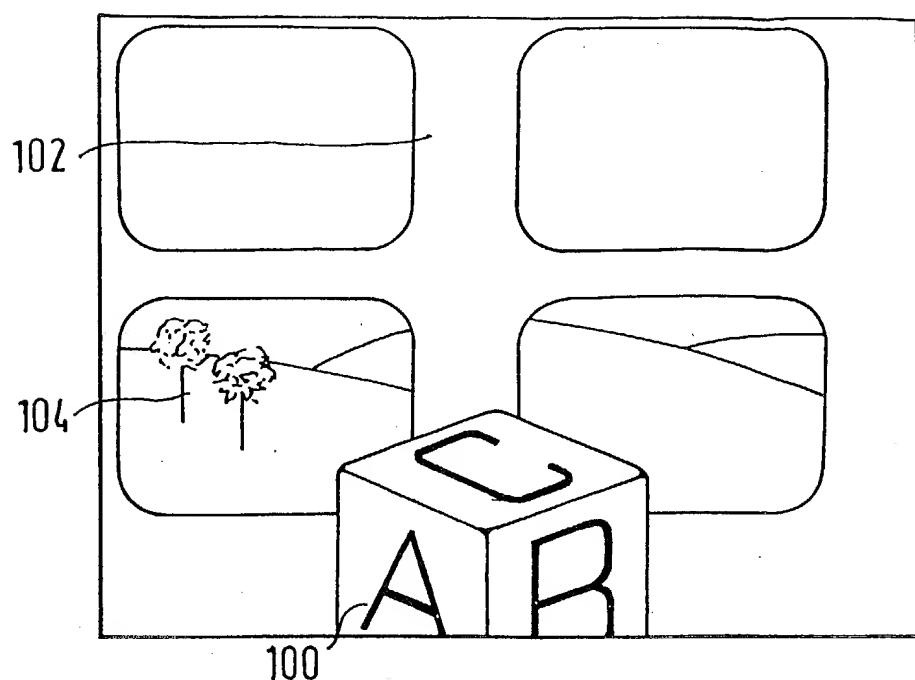
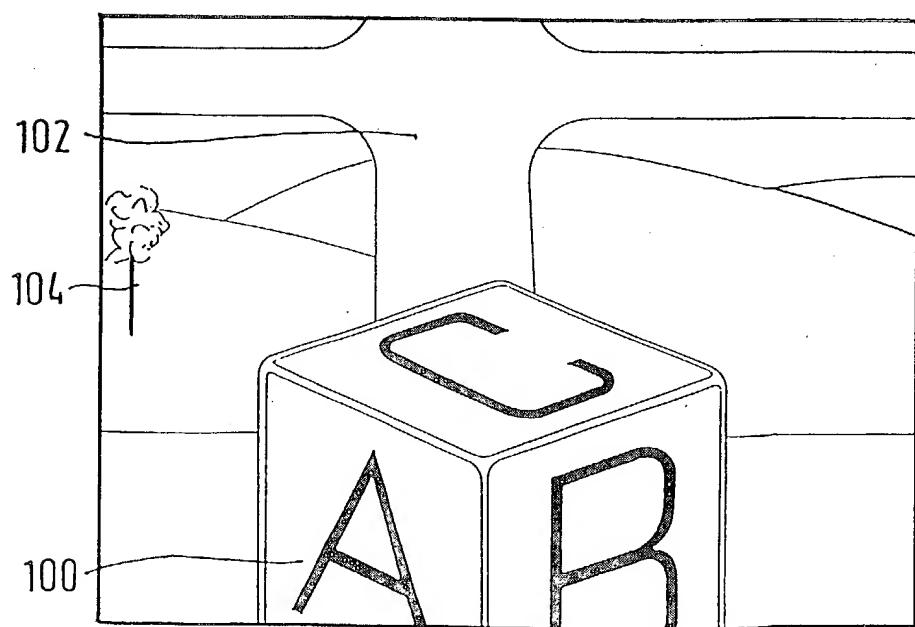


FIG.4



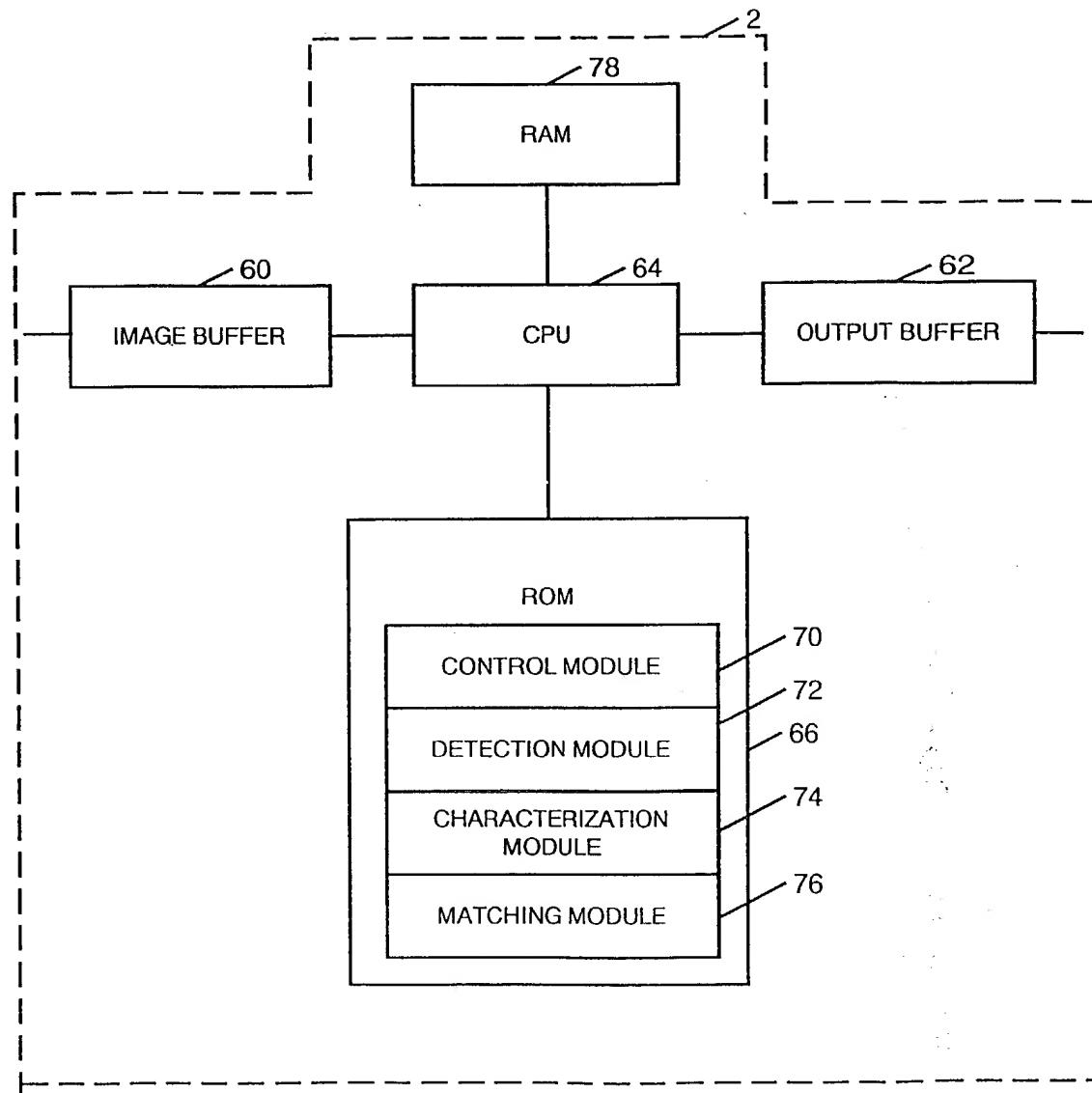


FIG. 5

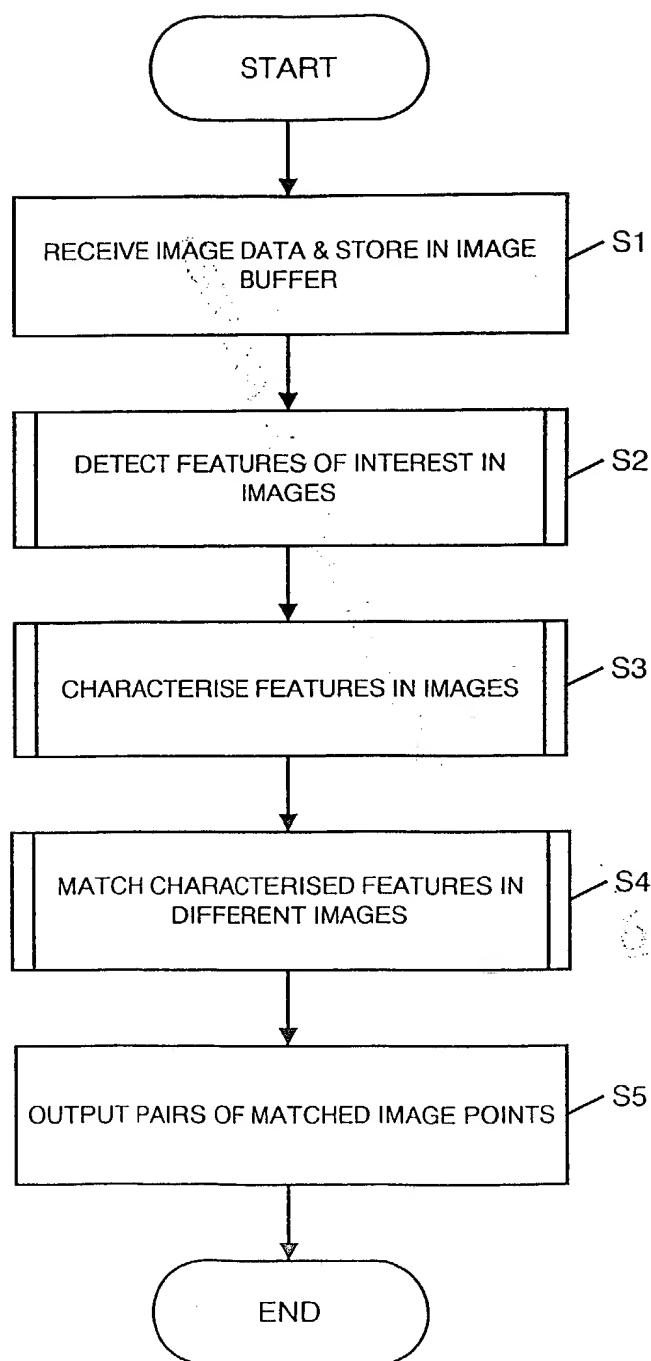


FIG. 6

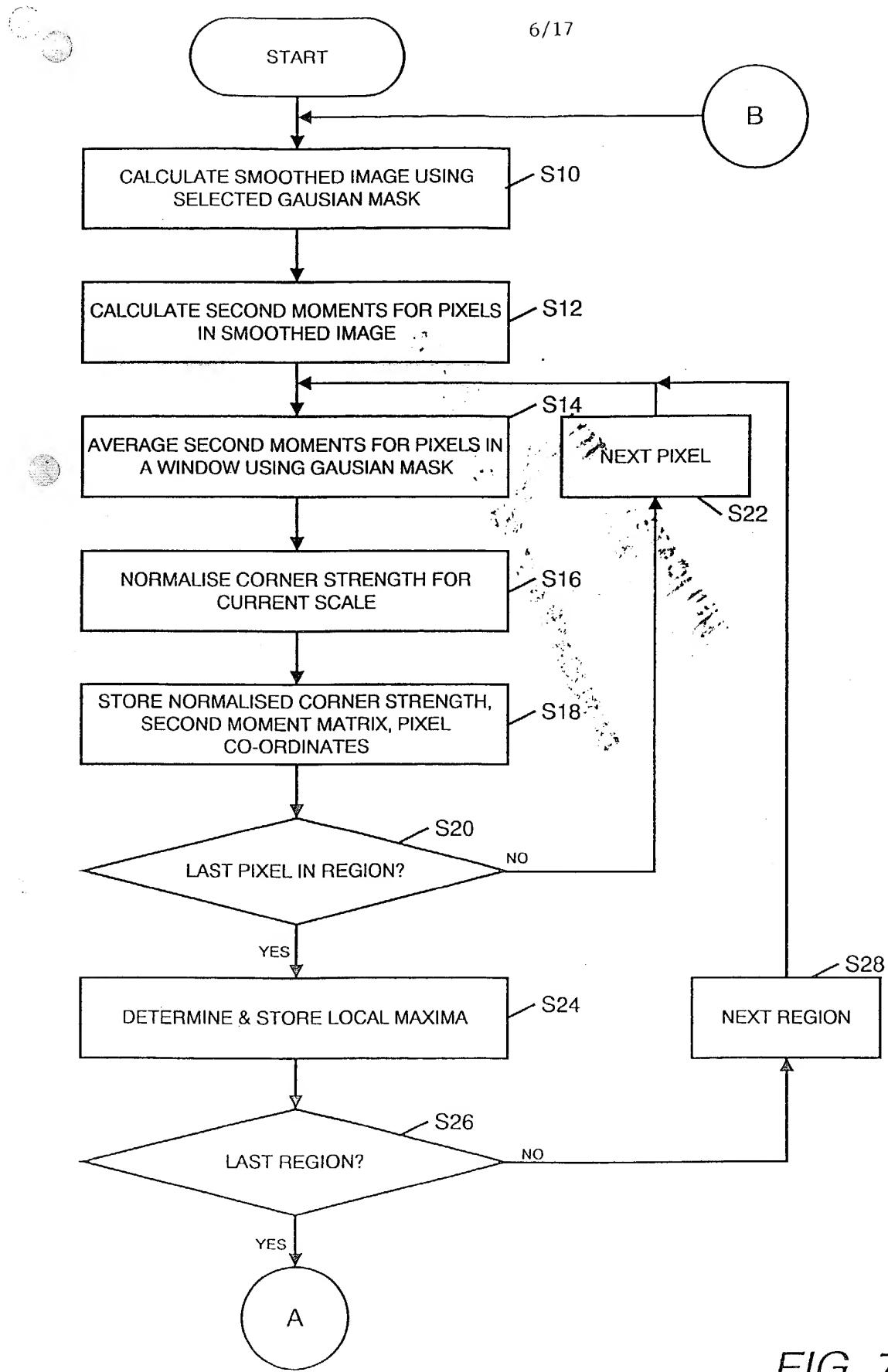


FIG. 7A

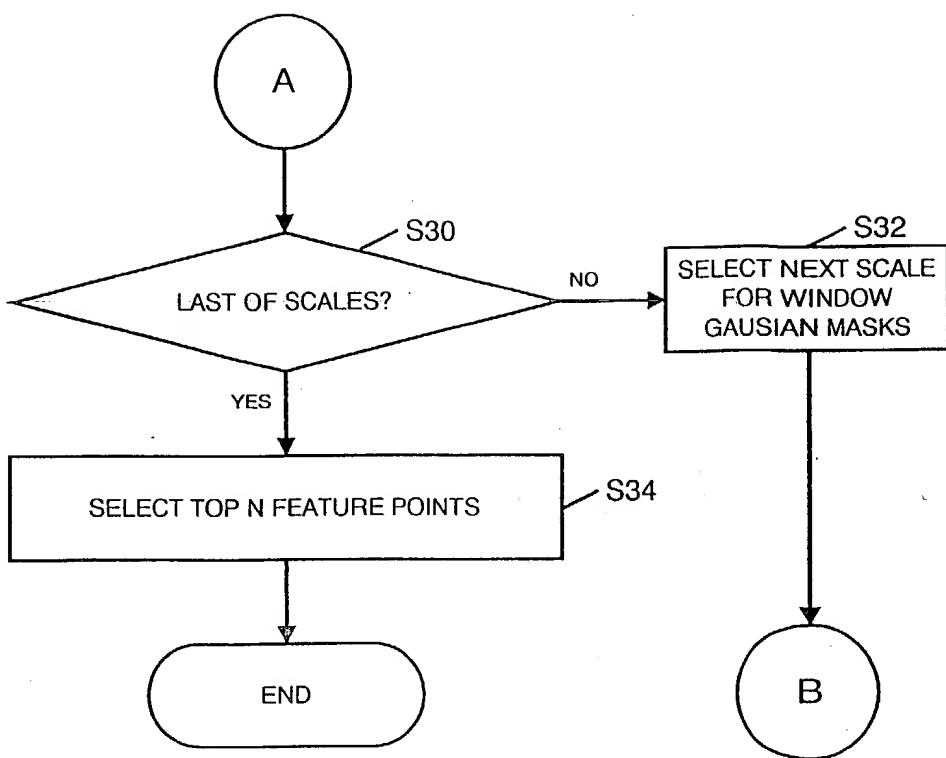


FIG. 7B

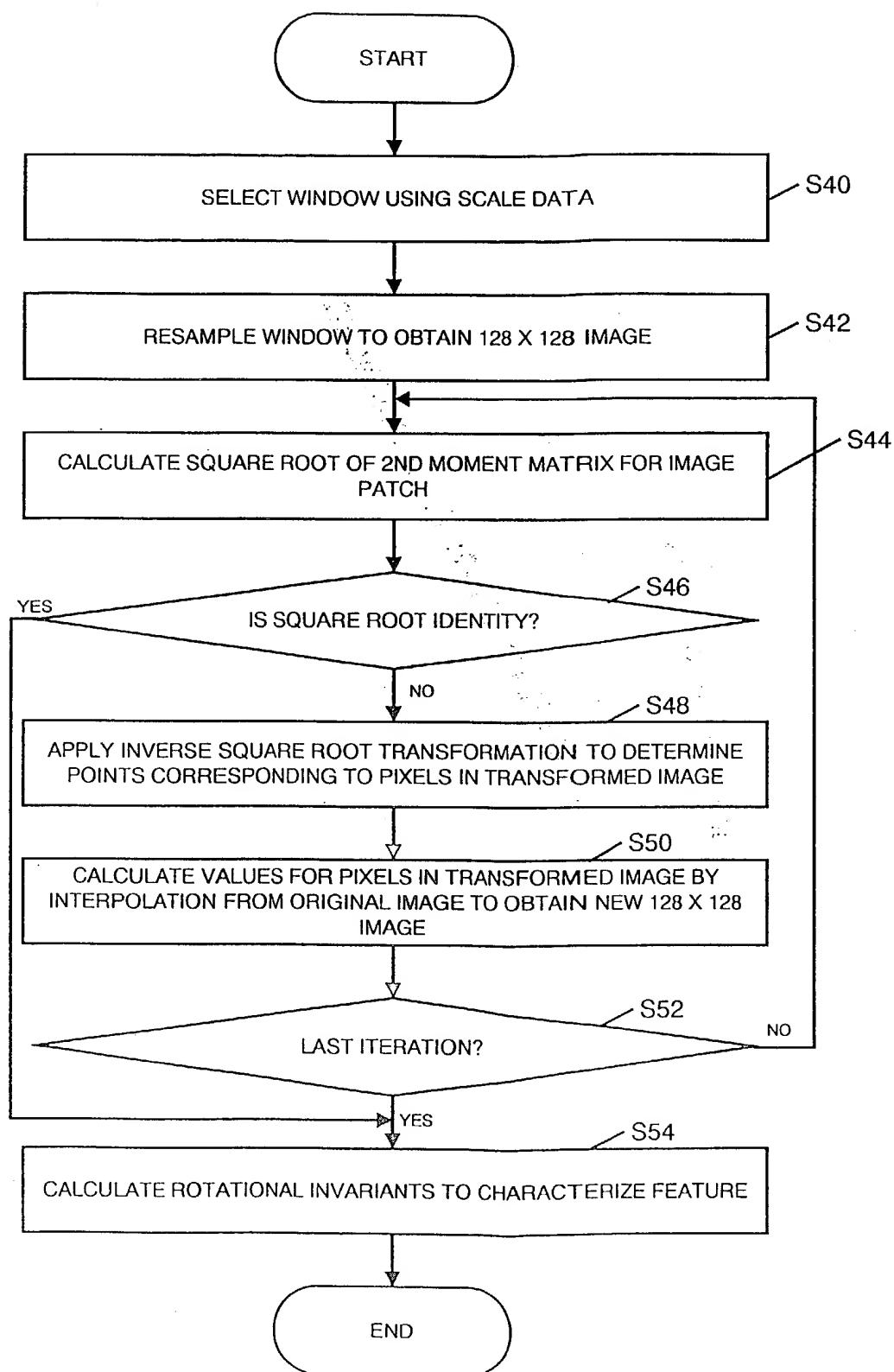


FIG. 8

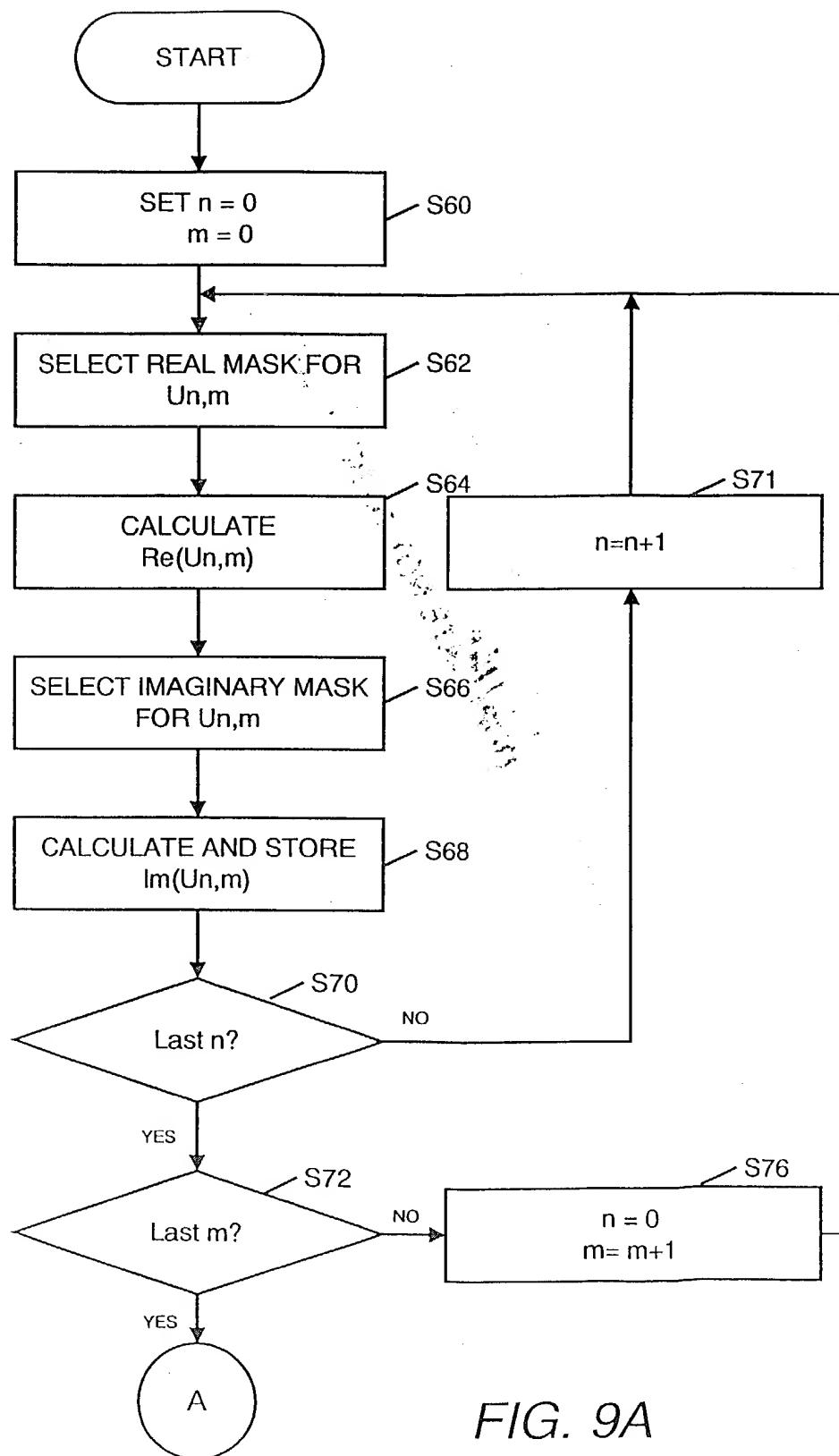


FIG. 9A

A

10/17

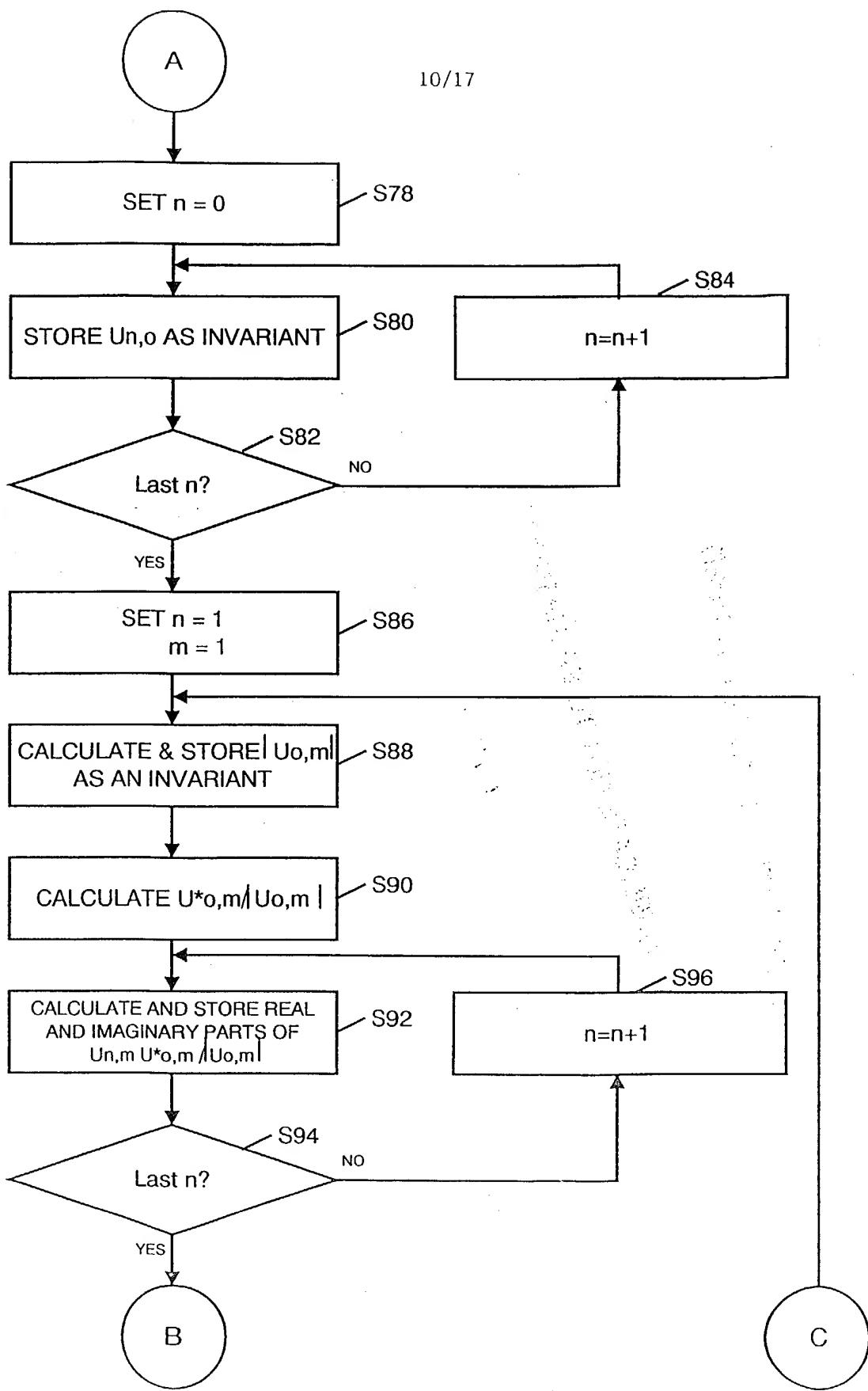


FIG. 9B

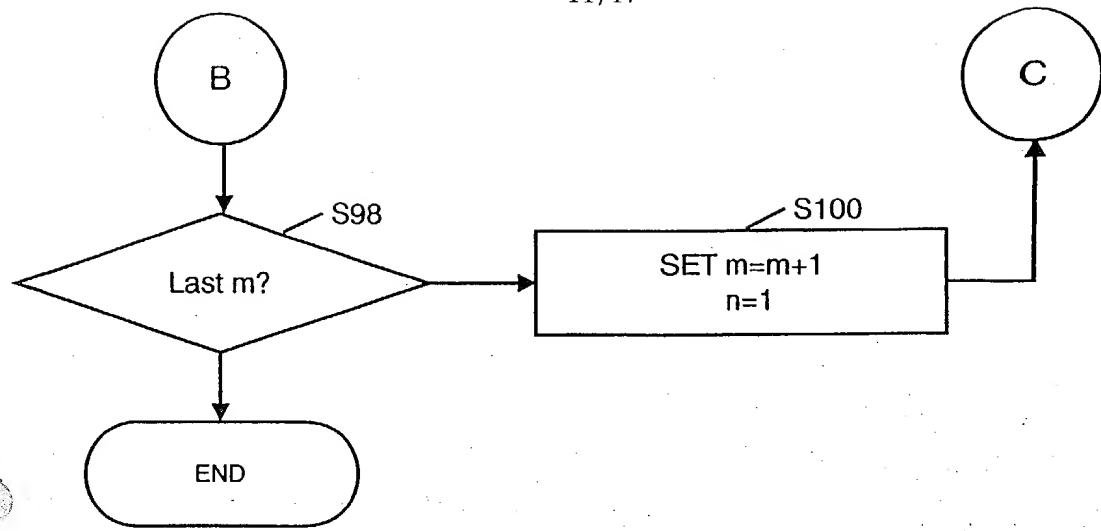


FIG. 9C

12/17

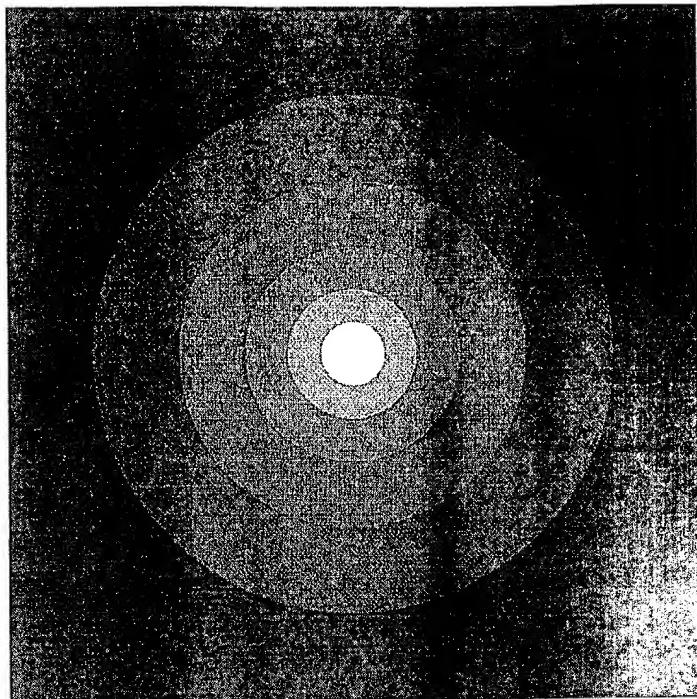


FIG. 10

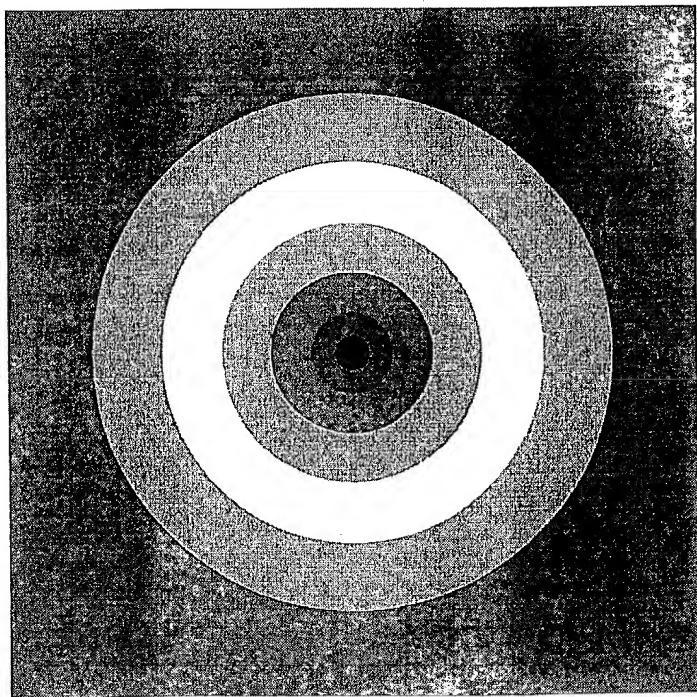


FIG. 11

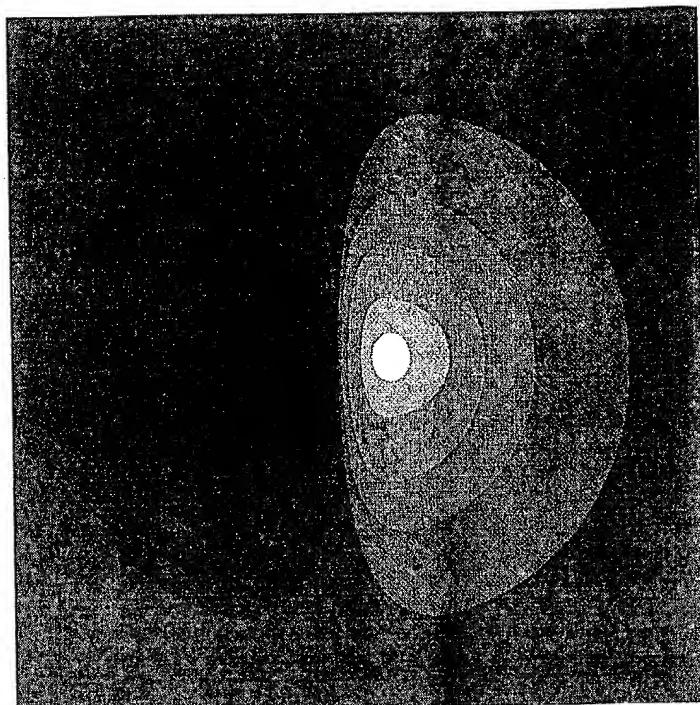


FIG. 12A

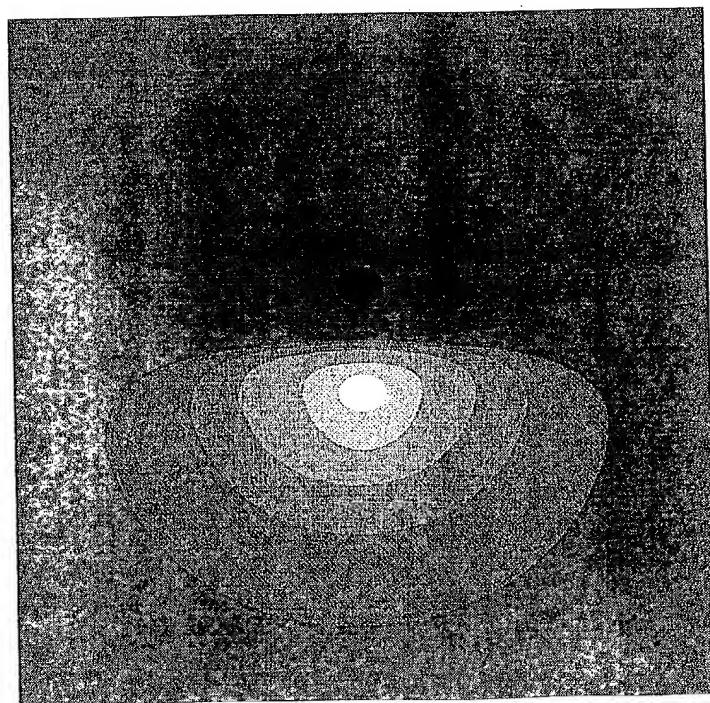


FIG. 12B

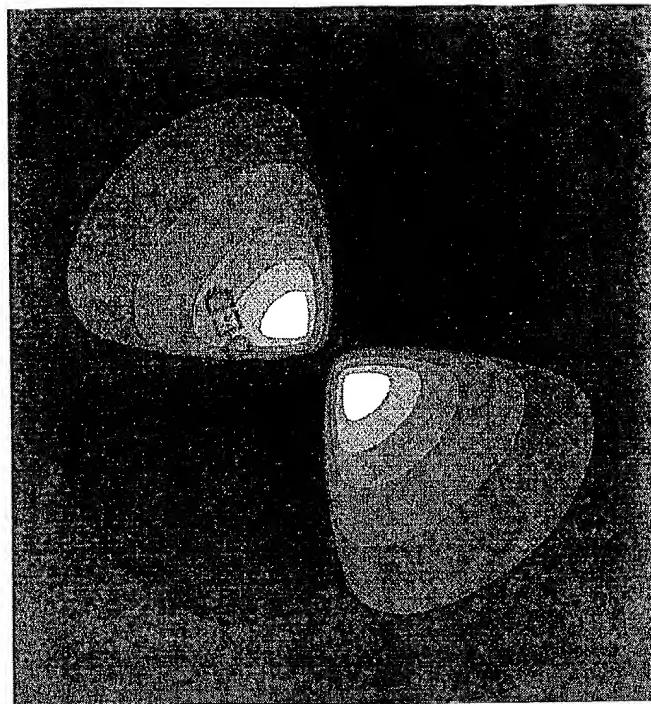


FIG. 13A

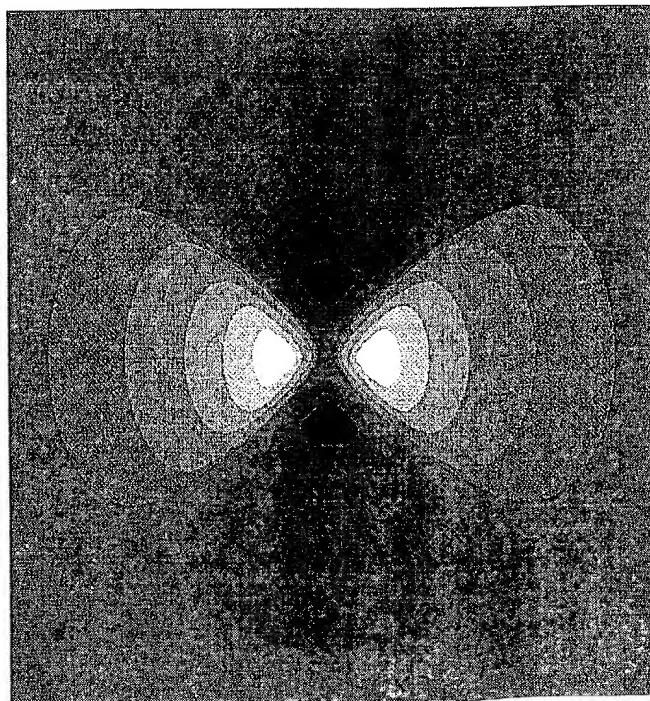


FIG. 13B

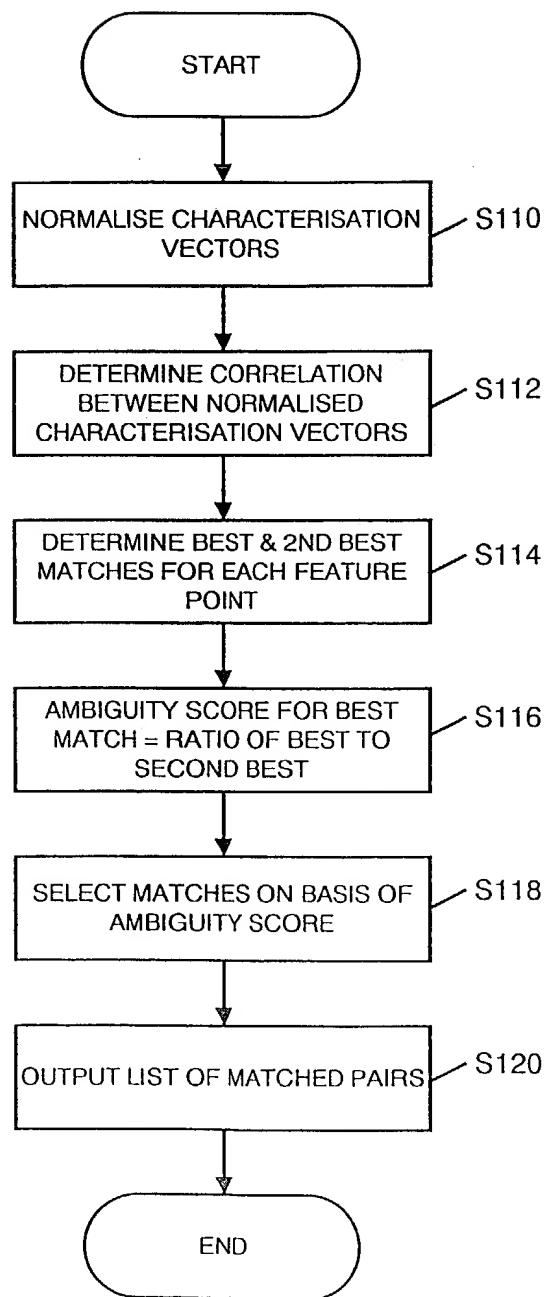


FIG. 14

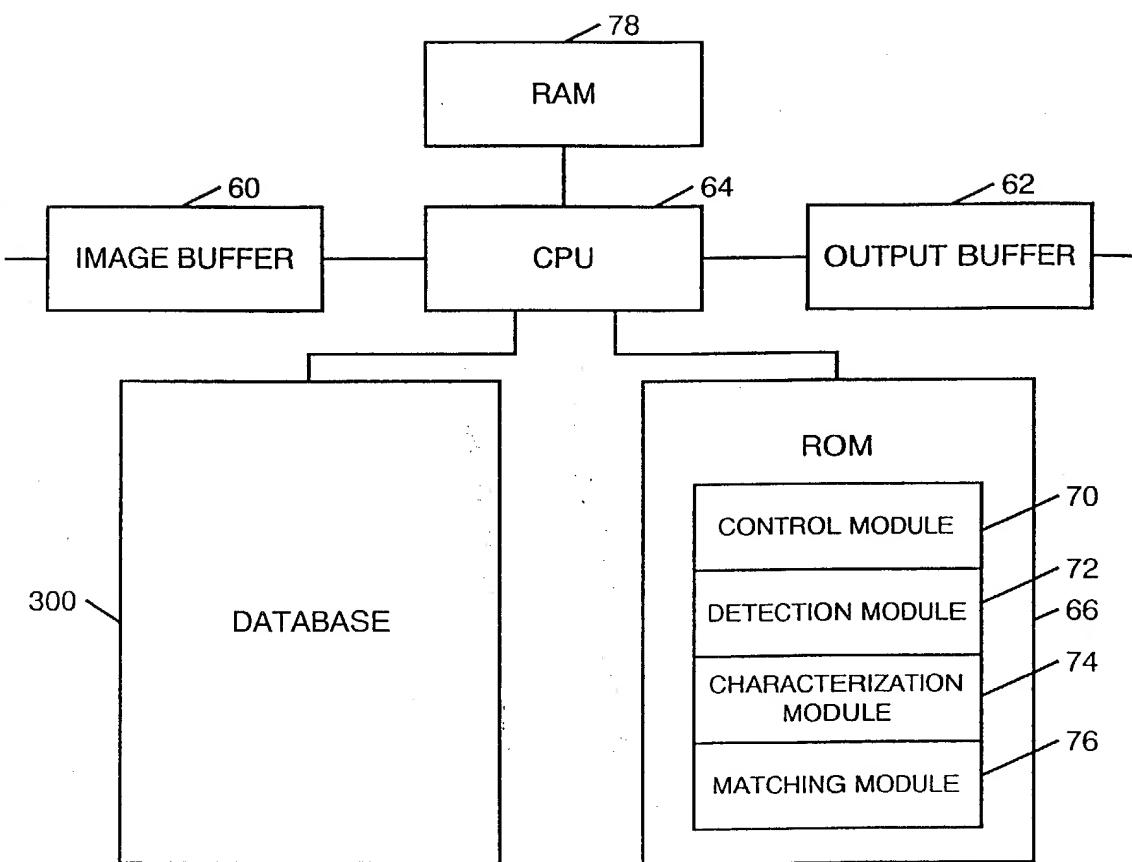


FIG. 15

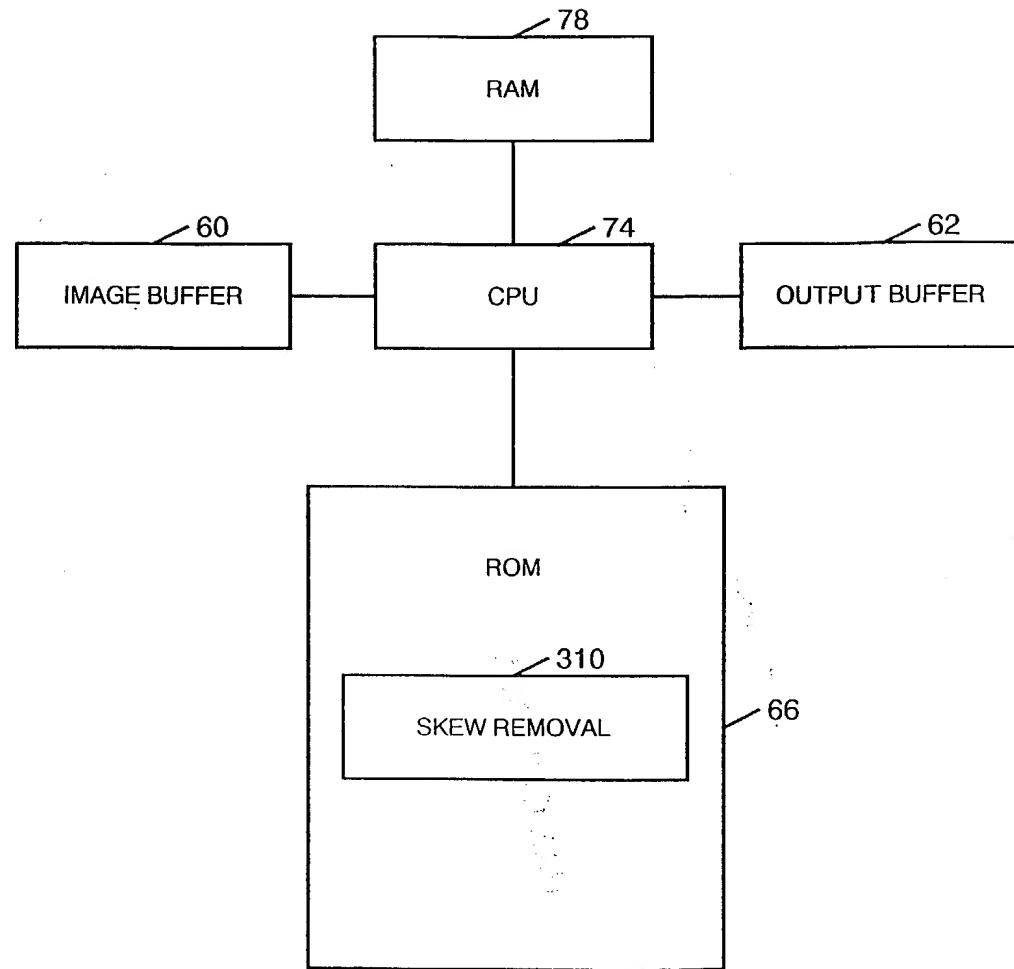


FIG. 16